Letter Report
TLR-RES/DE/REB-2022-05

Advanced Manufacturing Technology Components for Advanced Fuel Assemblies

August 2022

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Prepared as part of the Task Order 31310019N0006-31310020F0060, "Technical Support for DOE Component Integrity Codes, Graphite for ANLWRs, and AMT"

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INL/LTD-21-50361
Revision 0

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Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy.

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Prepared for the
U.S. Nuclear Regulatory Commission
Under DOE Idaho Operations Office
Contract DE-AC07-05ID1451

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ACRONYMS

AM	additive manufacturing
AMM	advanced method of manufacturing
AMT	advanced manufacturing technology
ASME	American Society of Mechanical Engineers
ATF	accident tolerant fuel
BJT	binder jetting
BPVC	Boiler and Pressure Vessel Code
BWR	boiling water reactor
CHF	critical heat flux
CIJ	continuous inkjet
CNUR	current nuclear usage rating
CVCS	chemical and volume control system
CVD	chemical vapor deposition
DED	direct-energy deposition
DOE	Department of Energy
EPRI	Electric Power Research Institute
GMAW	gas metal arc welding
HTGRs	high-temperature gas-cooled reactors
ISO	International Standards Organization
LWR	light water reactor
MBE	model-based enterprise
MOX	mixed oxide (fuel)
MRL	Manufacturing Program's Manufacturing Readiness Level
NAR	nuclear applicability rating
NEI	Nuclear Energy Institute
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
ONB	onset of nucleate boiling
ORNL	Oak Ridge National Laboratory
PVD	physical vapor deposition
PWR	pressurized water reactor
TCR	Transformational Challenge Reactor
TRL	Technology Readiness Level
TRISO	tristructural isotropic
TVA	Tennessee Valley Authority

ABSTRACT AND ACKNOWLEDGEMENTS

Advanced manufacturing is rapidly growing and demonstrating increased success in multiple industries like aerospace, biomedical and automobile industries. The success of these industries has inspired the nuclear industry to investigate advanced methods of manufacturing applications, although actual in-reactor operational demonstrations are too few and at a too slow pace to have a drastic impact on the economics and reliability of the nuclear industry. The niche nuclear market, with its unique high-performance parts, can potentially benefit from advanced manufacturing technologies (AMTs) if the technology is adequately developed. The future of the nuclear power industry will be filled with new types of reactors characterized by use of molten salt, high temperatures, gas cooling and other new technologies; however, reactor developers will continue to be risk averse in decision-making because few of these AMTs have been fully qualified for advanced reactor designs.

Beyond part performance, nuclear power can benefit from the potential manufacturing flexibility inherent in some AMTs. Nuclear power plants (NPPs) have several special safety-related valves, pumps, components, and, of course, material challenges. The market for these specialized components and materials is limited, making conventional batch-manufacturing processes, centered as they are on casting and machining, very expensive. This complicates the supply chain. AMT offers the opportunity to fabricate unique components one at a time, as needed. The capability to qualify individual parts using AMT will remain a challenge. Further, improved materials, geometries, and part consolidation will benefit all nuclear power systems. The harsh environment present in a nuclear reactor—particularly coolant chemistry, intense radiation fields, and high temperature gradients—make improved materials and advanced coatings particularly valuable.

This technical report describes the state of technology and applications of AMTs for nuclear reactor components and advanced fuel assemblies. Due to a recent acceleration of alternative advanced reactor demonstrations, an overview is provided of the current reactor landscape because fuels and associated fuel systems are significantly different, and they provide different opportunities for AMT applications. Background information on AMTs is collected to aid in the categorization of the large collection and variety of AMTs, and a summary of the categorization is provided in this report. Specifically, focused descriptions are provided on additive manufacturing processes and coating processes, as it is identified through stakeholder collaboration to have potential to have a significant impact on the acceleration of AMT deployment in niche nuclear reactor applications.

With the rise of automation and artificial intelligence in AM technologies, co-design of printed electronics within one package becomes possible, making smart, internet of things (IoT), advanced digital devices (such as implanted nuclear sensors within the reactor or fuel etc.) instinctively flexible and autonomous. Optimizing the processing parameters within the digital twin would lead to components with the required quality. Another application to machine learning is to propagate uncertainty.

However, there are several challenges related to rapid qualification, licensing, and commercial viability of AMT components in the nuclear industry. Further research and development initiative would help overcome these key technical challenges, with huge expansion of the materials for AMT in the future, that will comprise composites, functional materials, active and biological materials, and implanted micro/nano sensor and devices. The fundamental research on the stability of AM parts used in the extreme high temperature and hostile radiation environments, including high pressure, erosion and wear, fatigue, and the presence of wreckage and debris, is indispensable to the extrapolation of materials performance, properties, and lifetimes.

This report was sponsored by the U.S. Nuclear Regulatory Commission (NRC) Under DOE Idaho Operations Office Contract DE-AC07-05ID1451. The authors thank James Corson and Matthew Hiser from the NRC for their critical review and insights that enhanced the quality of the report.

1 INTRODUCTION

The gradual rise of global energy demand is estimated to increase by nearly 50% between 2018 and 2050, and the industrial sectors—including energy, manufacturing, oil and gas, mining, construction, and agriculture—face more than a 30% surge in energy consumption [1][2]. Advanced manufacturing and related upscaling technologies, particularly aiming at scalable, clean, and green-energy options—for example, solar[3], wind[4], energy storage[5], and nuclear [6]—are expected to be strategic solutions.

The nuclear power sector can potentially benefit from AMTs [2][7]. The improvements in performance for components fabricated with advanced technologies are commonly expected over conventional manufacturing processes [8]. The niche nuclear market, with its unique high-performance parts, could especially benefit from advanced manufacturing. The future of the nuclear power industry is expected to include new types of reactors characterized by use of molten salt, high temperatures, gas cooling and other new technologies; however, reactor developers will continue to be risk averse in decision-making because few of these AMTs have been fully qualified for advanced reactor designs. These new technology reactors could especially benefit from AMT to support their initial deployment and rollout into the market [9]. Improved materials, geometries, and part consolidation will benefit all nuclear power systems. The harsh environment present in a nuclear reactor—particularly coolant chemistry, intense radiation fields, and high temperature gradients—make improved materials and advanced coatings particularly valuable [11].

Beyond part performance, nuclear power could benefit from the potential manufacturing flexibility inherent in some AMTs. NPPs have several special safety-related valves, pumps, components, and, of course, material challenges [12][13]. The market for these specialized components and materials is limited, making conventional batch-manufacturing processes, centered as they are on casting and machining, very expensive. This complicates the supply chain [14]. AMT offers the opportunity to fabricate unique components one at a time, as needed [15]. Producing single components as needed could simplify the supply chain and allow updates in components as needed. Improved supply chain performance will also allow improved economics as large batch processing is replaced by more-complex, individual, single fabrication and complex part qualification.

Advanced manufacturing is rapidly growing and demonstrating increased success in multiple industries. A notable example is General Electric's three-dimensional (3D) printing of fuel-injector nozzles and engines for airplanes. The success of these industries has inspired the nuclear industry to investigate advanced methods of manufacturing applications.

This technical report describes the state of technology and of practice in applications of AMTs for advanced fuel assemblies. Due to a recent acceleration of alternative advanced reactor demonstrations, an overview will first be provided of the current reactor landscape (Section 2) because fuels and associated fuel systems are significantly different, and they provide different opportunities for AMT application. Background information on AMTs is collected to aid in the categorization of the large collection and variety of AMTs, which are reported separately in a review paper (under preparation and will be communicated soon). Only a summary of the categorization is provided in this report. Specific discussion of AM and coating technologies are provided in this report, as these AMTs are identified to have significant impact on the acceleration of new and advanced reactor systems.

2 | REACTOR TYPES

The characteristics of reactors discussed in this section are summarized in Table 1. The non-LWR landscape, as reported by the Nuclear Regulatory Commission (NRC), is shown in Figure 1.

Table 1. *Summary of various reactor types and their high-level characteristics.[16][17][18]*

Reactor Type	Coolant	Spectrum	Power Range	Outlet Temperature Range
Light Water Reactor	Water	Thermal	Up to 1.2GWE	~ 300 C
Liquid Metal Reactors	Sodium, Sodium-Potassium, or Lead-Bismuth	Fast	Up to 1.2GWE	>500-600 C
High-Temperature Gas-Cooled Reactor (HTGR)	Helium (typically)	Thermal	40-330MWE	~700-800 C
Molten Salt Reactor (MSR)	Fluoride- or Chloride-Based Salt	Thermal or Fast	Up to 300MWE (SMR size)	~600–800 C
Microreactor	Various	Thermal or Fast	<10MWE	630-700 C

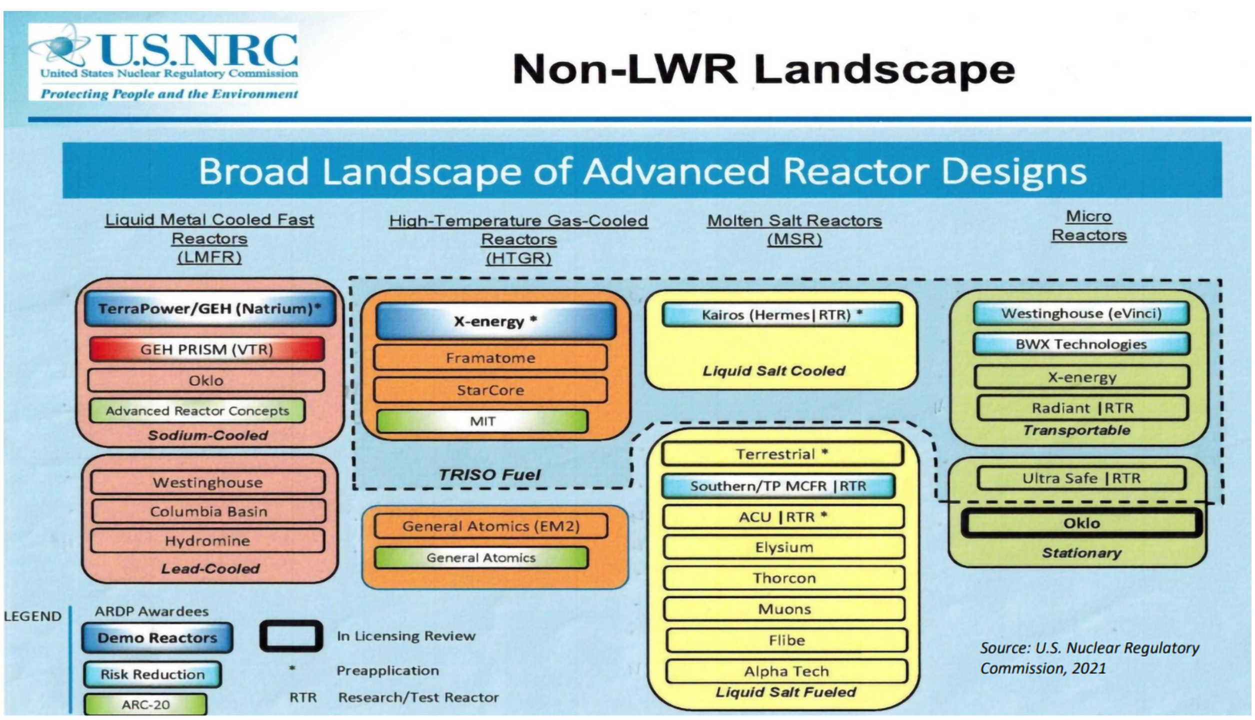

Figure 1. *The non-LWR landscape [19].*

2.1 LIGHT WATER REACTORS

LWRs are the most commonly operated nuclear reactors; they currently constitute the entire U.S. fleet of nuclear power reactors and are historically the most-common reactor type worldwide. Advanced LWRs like the NuScale NPP are being developed.

"Light water" means water composed of naturally occurring hydrogen, where ~99.9% is ^{1}H, a single proton nucleus. This makes the water very efficient at slowing neutrons created in fission reactors to speeds at which they can more-easily interact with other atoms. An LWR uses light water as both neutron moderator and coolant.

Each neutron-induced fission reaction generates multiple neutrons; this allows an infinite chain reaction of fissions to occur, limited by the available fissile material. The nuclear fuel, typically uranium that has its ^{235}U content enriched, is separated from the coolant by an inert cladding. Separating fuel from coolant improves neutron efficiency at creating fissions and, most commonly, forms fuel into plates and cylinders. Using the same material for cooling and moderation simplifies reactor design.

The large operating experience using water in conventional combustion power plants and nuclear reactors can be applied to the design of new NPPs. High-temperature and pressure water also has well-known corrosion, safety, and operating issues when used inside an NPP.

The reactor vessel contains fuel, instruments, structure, and control rods that allow controlled power production at an NPP. Water circulates through the core, propelled either by pumps or natural circulation. As water passes through the core, heat produced by fission reactions raises the temperature of the water, which is pressurized. This allows higher temperatures and enables the steam power cycle.

2.1.1 PRESSURIZED WATER REACTORS AND BOILING WATER REACTORS

Commercial LWRs operate as PWRs and BWRs. In PWRs, water heated in the core, the primary loop water, transfers heat to a secondary loop of water in a steam generator. The primary water cooled in the steam generator returns to the reactor core to be heated again. The steam in the secondary loop of a PWR generates power using a turbine and generator set. In a BWR, water in the core can boil. The steam generated in the core is separated from any entrained water and then used to directly drive a turbine/generator set. Steam that was used to drive the turbine is condensed and recirculated to reactor (Figure 2).

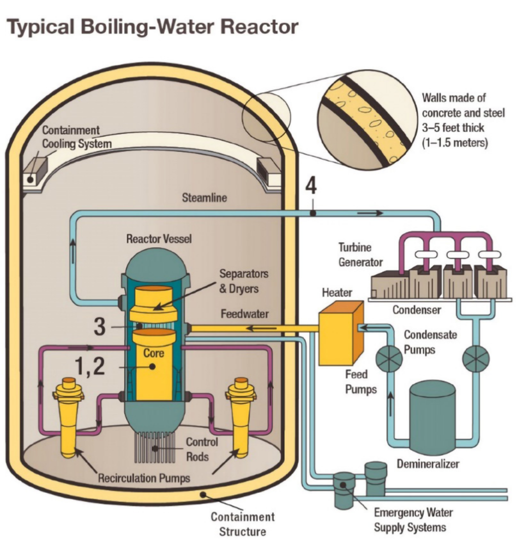

Figure 2. *Typical BWR showing simplified steam loop.[20]*

Movable arrays of control pins and (boron) neutron absorbers dissolved in the coolant in PWRs, and of cruciform blades and the core flow rate in a BWR, allow control of the neutron level that, in turn, controls the reactor's power level. PWRs also dissolve boron, an efficient neutron absorber, directly into the coolant to inhibit the neutron population. Multiple factors—pressure, temperature, void content—can also affect power levels in the core. This makes operation of the core a potentially complex endeavor.

2.1.2 LWR NUCLEAR FUEL SYSTEMS

The fuel currently used in an LWR NPP is UO_2 ceramic pellets stacked into pins. The pins are arranged in an array established by top and bottom plates, with spacers to maintain reactor geometry. The array of pins and structures forms a fuel bundle (Figure 3). Careful arrangement of fuel enrichment and neutron absorbers within a bundle and arrangement of the bundles in the core allow the reactor to perform safely for up to 2 years between reloading. Approximately one third of the core is replaced each outage. Fuel can be used for more than three operating cycles.

LWRs have a long history of development and progress of the nuclear fuel system used. Modern LWRs use UO_2 fuel pellets, approximately 10 mm in diameter, with a less than 1mm thick zirconium alloy cladding. UO_2, enriched to less than 5% ^{235}U, is used for its low-neutron-absorption cross-sections and robust strength. UO_2 has the disadvantage of having poor thermal conductivity, which raises the centerline fuel temperatures. The fuel in the pins is nearly 4 meters tall. These pins are assembled into bundles. The bundle holds the pins in a fixed lattice to maintain nuclear properties. The spacing of the pins is set by the top and bottom plate and a series of spacer grids. In modern reactors, individual pins can have different enrichments and contained poisons—i.e., boron or gadolinium—to control power level and shapes. The enrichment and poisons can vary within a single pin in some designs. Selected pins, especially in BWR reactors, can be shorter for thermal-hydraulic reasons. Some pins are replaced by instrument tubes. The power shape is managed by internal poisons and control rods to ensure safe operation.

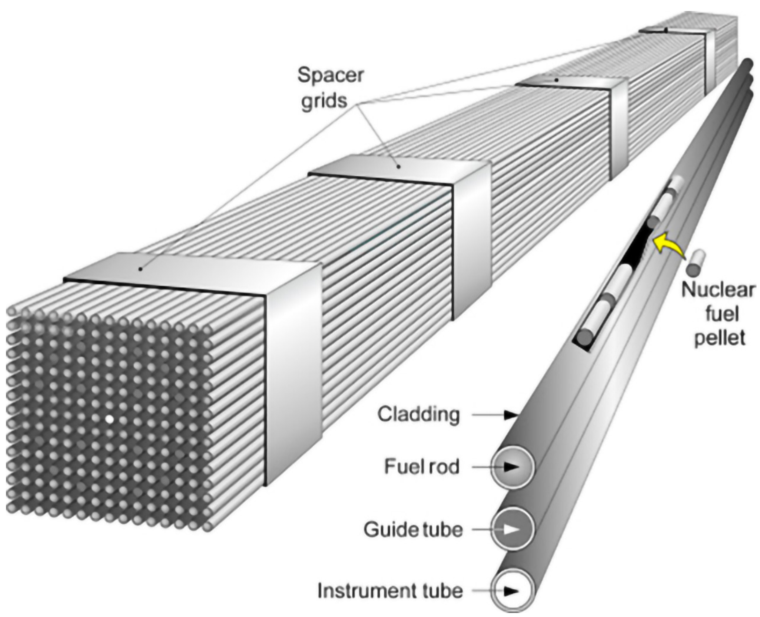

Figure 3. *Schematic of the LWR fuel pins and assembly[21].*

LIQUID-METAL-COOLED REACTORS

Replacing the water coolant with a liquid metal, like sodium or lead, allows for relatively high-temperature, low-pressure systems. Sodium-cooled reactors are a well-established technology, with a long history (Figure 4). Carefully designed, liquid-metal-cooled reactors (LMRs) display inherent safety and unique operating performance [22]. LMRs are traditionally operated without slowing the neutrons (i.e., in the "fast-neutron" spectrum).

Fast-spectrum neutrons change the way uranium and other nuclear fuels are used in the reactor. Fast LMRs use liquid metals, such as sodium, lead, or lead-bismuth, as a coolant. This enables operation at higher temperatures and lower pressure than are seen in PWRs because the coolant has high conductivity; therefore, LMRs show improved heat-removal capability. Because these designs create heat based on fissions primarily caused by high-energy (fast-spectrum) neutrons, the reactors can be operated to high depletion and could also operate with used fuel from other, current reactors to produce energy. This is because high-energy neutrons are not as easily absorbed in transuranic isotopes present in depleted fuel as are thermal energy neutrons. However, fast-spectrum neutrons also make reactor shielding more difficult.

LMRs have historically operated in the several countries; existing plants are currently in operation primarily in Russia, and new LMR concepts are currently under development. The liquid-metal coolant is pumped by electromagnetic pumps (with no moving parts) through an intermediate heat exchanger or steam generator before returning to the core. Reactivity control is typically achieved with controls rods composed of neutron-absorbing material (e.g., B4C).

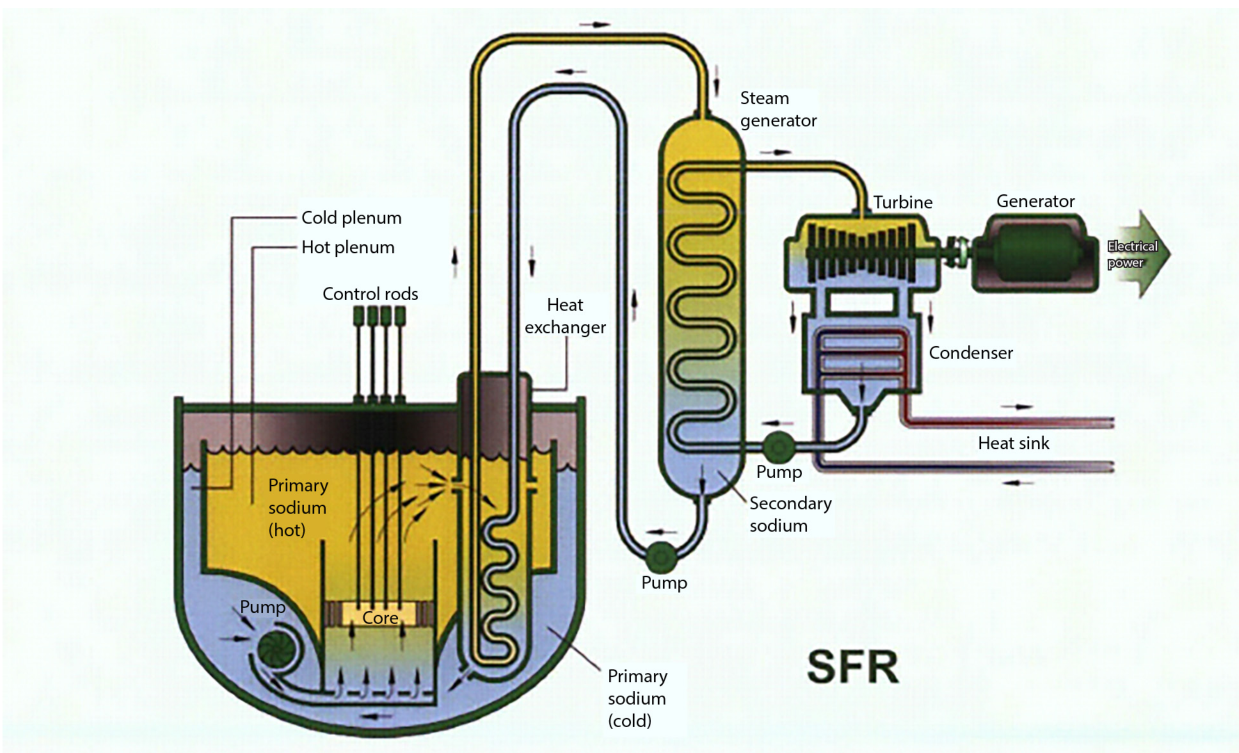

Figure 4. Sodium-cooled fast reactor schematic [23].

2.1.3 FAST REACTOR FUEL SYSTEMS

Fast reactor fuel can vary, but each emphasizes the use of high-density fissile material having increased uranium or plutonium helps make up for the lower probability of fission in fast reactors. Uranium dioxide fuel is often used with enriched uranium because of its familiarity in reactors. Metal fuels are used in lower-temperature systems, and they benefit from high fissile density and low resistance to heat transfer. Higher-temperature LMRs tend to look at nitride or various stoichiometry carbide fuels. The carbide and nitride fuels allow higher fissile density and easier heat transfer than can oxide fuels. Carbide and nitride fuels tend to swell and continue to be complex to produce. [24]

Historical testing has been performed on sintered UO_2 pellets or mixed oxide (MOX, i.e., plutonium and uranium oxide) pellets. Modern industry designs in the U.S., as well as metal-alloy fuels such as U-Zr and U-Pu-Zr, produces fuel in the form of cylindrical slugs. These slugs are thermally bonded to the cladding using liquid-metal sodium.

LMR reactors make heavy demands on cladding performance. The inherent fast-neutron irradiation embrittles and damages cladding up to a hundred times as much as in a thermal reactor. The amount of damage tends to enhance creep. The use of stainless steel cladding has largely been required for chemical and structural benefits. The detailed chemistry to resist mobility of atoms and voids leads to potential additions of alloying elements. The higher absorption of neutrons in iron alloys is less important in fast reactors than in LWR because of the lower overall probability of neutron interaction. Typically, fuel is loaded into pins clad with stainless steel (SS 316). Other alloys, e.g., HT-9, have been used. Accident tolerant fuel studies and high-entropy alloys could benefit LMR cladding. Structural core components also suffer from high doses and damage, and improvement in cladding material could help with core component design [25].

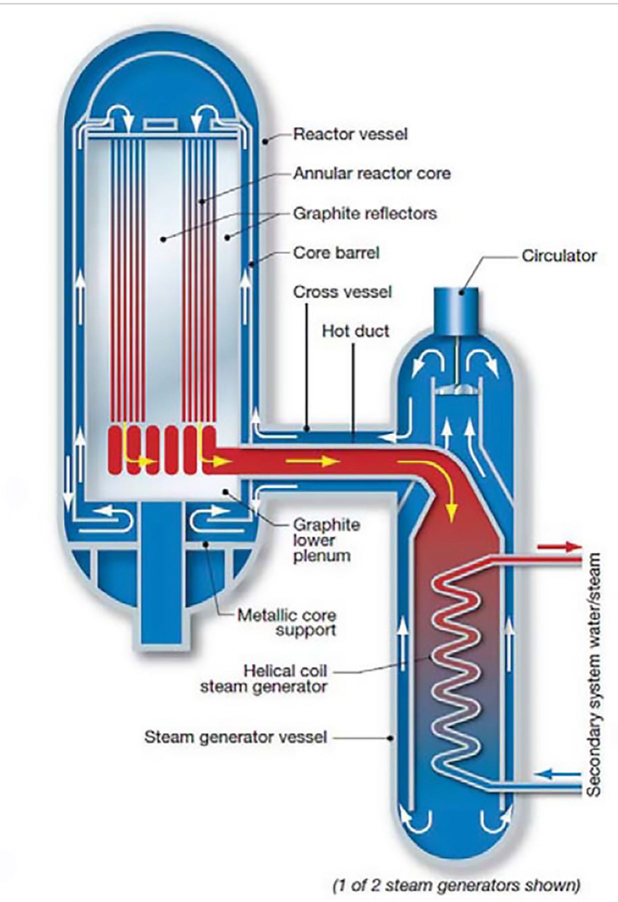

Figure 5. *Modular high-temperature gas-cooled reactor schematic [26].*

2.2 HIGH-TEMPERATURE GAS-COOLED REACTOR

HTGRs have been successfully operated in the U.S. in the past. While no U.S. plant is currently in service, several HTGRs continue to operate worldwide. Additionally, new HTGR designs are being developed.

HTGR fuels are typically composed of UO_2 or UC in graphite (or pyrolytic carbon) compacts or spheres, encapsulated in layers of SiC (thus, tristructural isotropic [TRISO]), cooled by high pressure helium. The helium coolant is not a sufficient moderator, so thermal-spectrum HTGRs will often include graphite as moderator in thermal-spectrum designs. Unmoderated (fast-spectrum) HTGR designs are also possible. The coolant temperature in HTGR designs is typically between 700 and 950°C.

Reactivity control is achieved with control rods, either inserted into fuel blocks, the reflector region, or a pebble bed, depending on the design. The primary coolant can be piped (direct cycle) to one or more steam generators or other heat exchanger (indirect cycle) depending on the power-conversion system (Figure 5).

2.2.1 FUEL SYSTEMS FOR HTGRS

Most HTGRs use carbon to thermalize the neutrons and provide very-high-temperature capability. The large distances that thermal neutrons travel in very-low-absorption carbon reduces the need to have a high fissile element density. Dispersed fuels and minute fuel particles distributed in fuel forms work well in HTGRs. The low fuel density also drives down power densities, creating large cores with high inherent fuel safety limits [27].

A unique approach to microparticle fuels further improves the potential safety of HTGR reactors. Improved fuel performance can be achieved by TRISO fuel, with its advanced engineered features. Combinations of nuclear fuel and structural materials, each performing an individual task, creates a better fuel form. A microsphere of nuclear fuel is coated in thin layers of buffer material (i.e., carbon) and structural material (silicon carbide). These layers provide high-temperature containment at the microlevel for nuclear fuel. Merging massed microspheres into compacts of carbon, TRISO fuel presents fuel forms that can be used in reactors. The lower overall density of the nuclear fuel makes TRISO another example of the need to match reactor design to fuel. HTGR reactors have been a successfully designed to use TRISO fuels [28].

2.3 MSRs

Replacing water with halogen low-temperature melting halogen salts a reactor allows higher temperatures and lower pressures. Molten salt provides a good heat transfer mechanism, with very low vapor pressure. A low vapor pressure allows the molten salt to be used at near ambient pressures, simplifying reactor design. Molten salts display low corrosion rates given the correct nuclear materials. The fuel can be a liquid dissolved into the coolant salt. The molten fuel/coolant mixture offers unique operating benefits because the fuel can continuously be managed for fissile materials and fission products. More-conventional designs, with solid fuel, are also possible. MSRs are well suited to high-temperature operation. Molten salts can be used for heat storage, allowing MSR designs to easily incorporate such systems.

Due to their higher operating temperatures and online fuel reprocessing, MSRs could use resources more effectively and produce less radioactive waste. They have the potential to improve the economics of nuclear energy production by using a low-pressure coolant system and adding fresh fuel without lengthy refueling outages. Some MSR concepts could consume used fuel from other reactors, reducing the amount of material for disposal (see Figure 6).

No MSR is currently in operation; two were operated at Oak Ridge National Laboratory in the 1950s and 1960s.

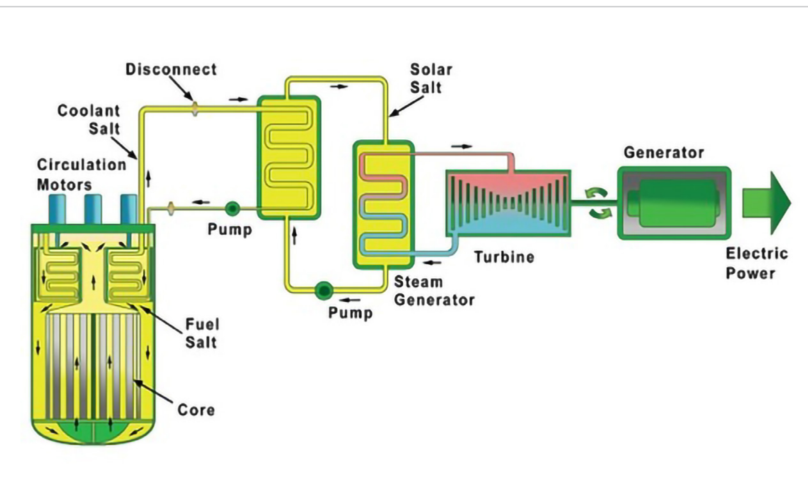

Figure 6. *Molten Salt Reactor [29].*

2.3.1 MSR FUEL SYSTEMS

For fueled-salt reactor concepts, the fuel is designed to achieve criticality in the reactor vessel and to transfer heat to an energy-conversion system via a molten salt heat exchanger. In either chloride or fluoride salts, chemistry-control systems are needed. Because the primary coolant is also the fuel, system maintenance that minimizes human exposure is needed. This design includes salt storage, where the fuel salt can be safely stored during shutdown. Reactivity-control concepts include shutdown elements to displace salt, reflector-geometry control, helium injection, or flow control.

2.4 MICROREACTORS

Microreactors differ from the previously described reactors, which are defined by the technology that allows the reactor to maintain a chain reaction. Microreactors are a class of reactors defined by their small power output—generally less than a few tens of megawatts electrical—and very robust designs. Test and research reactors are often small, but do not include the robustness of design and transportability that characterize microreactors (Figure 7). Microreactors are generally designed to have minimal accident consequences. They are factory built, potentially autonomous, and portable. These properties allow microreactors to support applications in remote locations, microgrids, industrial applications, and emergencies that are not addressed by larger conventional plants.

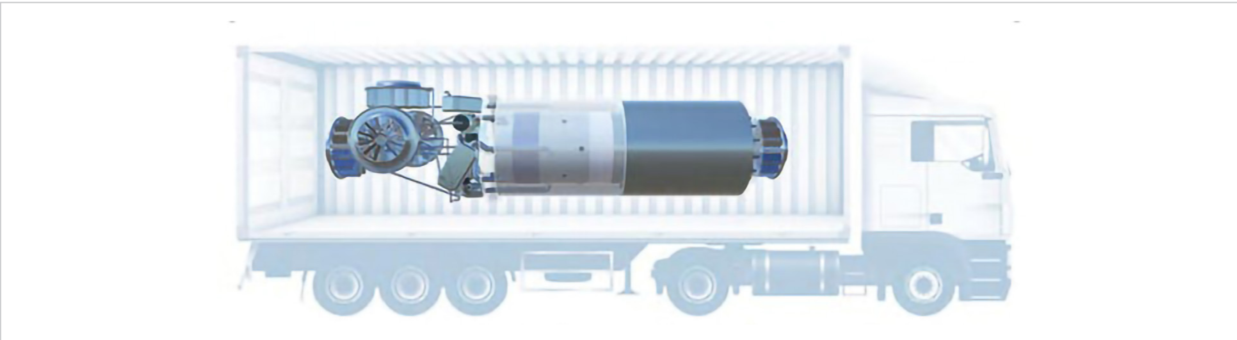

Figure 7. *Microreactor design showing portability features.*

2.4.1 MICROREACTOR DESIGNS

LWRs, MSRs, fast LMRs, HTGRs, and more-unusual reactor designs have been proposed for microreactor applications. Multiple U.S. designs are being developed for near-term demonstration to address Department of Defense applications, with commercial applications to follow shortly afterward. These reactors use unique technology combinations to produce heat and electrical power. Heat pipes are included in some designs to move power robustly from the core to power-generating equipment (Figure 8). Supercritical CO_2 power systems are often used in place of steam-driven systems. These new power systems need high-temperature materials. Very robust TRISO particles are also central to many designs. These new reactors are different enough from existing designs that the licensing framework for the reactors is being reconsidered.

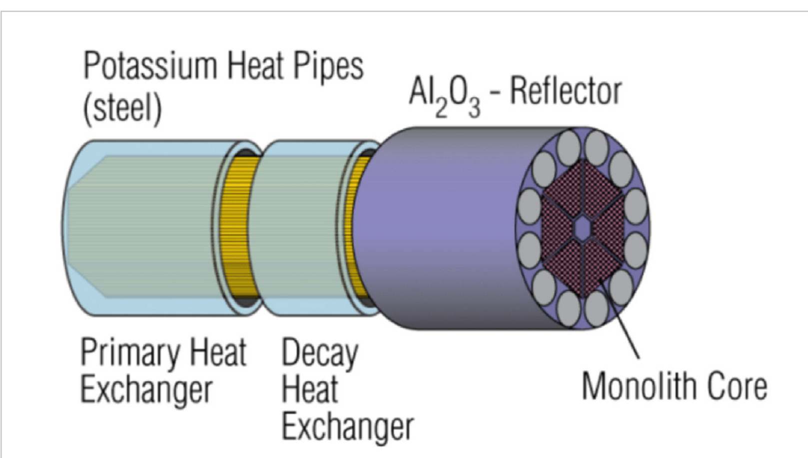

Figure 8. *Simplified microreactor schematic with heat pipes.*

Microreactors are being designed to be robust and simple so that they can be deployed into environments that lack infrastructure and support. This will allow the reactors to support power needs in remote locations or following natural disasters, when the grid is not available. Some current designs are built to be transported by rail, truck, or aircraft to allow them to reach remote locations. Transportability creates weight and volume restrictions for the shielding that surrounds a microreactor. Assembling precision shielding with layers of various high- and low-density materials makes deploying the reactors a challenge. Moderators with light elements, like hydrogen, can reduce weight by allowing the reactor to operate with less uranium fuel and a thermal-neutron spectrum, similar to an LWR. For moderators to be effective over the life of the reactor, they must remain stable, even at high temperatures. Deployment could take only a few days, instead of the years required for conventional NPPs. Microreactors would also be able to integrate their power with conventional power plants and renewables. Microreactors, owing to these technologies, could support local industrial applications, district heat, and desalination.

Higher-enrichment fuel, up to 20.0% ^{235}U, and small power output would allow the reactor to operate for years without refueling. The portability built into many designs would allow them to be replaced as a unit (that is, swapped out) when significant maintenance is eventually needed.

An ultimate expression of the microreactor is captured by the concept of a fission battery. A fission battery is a microreactor that is automated and self-directing to the point that it independently provides power to a local application. Fission batteries could be installed at sites and operate with minimum observation; thus, they would not require operating or maintenance crews. A fission battery requires the combination of new, highly safe nuclear and control concepts in a new type of reactor. These concepts are being developed to serve remote applications.

2.4.2 MICROREACTOR NUCLEAR FUEL SYSTEMS

Like microreactor technology in general, the nuclear fuel covers a number of technology systems. LWR microreactors use fuels similar to larger LWR reactors. Many microreactor systems use alloys of uranium to increase the density of the fuel. The fissile fuel density is also increased by using higher (i.e., up to 20%) ^{235}U enrichment fuel. High-temperature microreactors often use TRISO fuel systems (see Section 2.3.1). These carbon compacts with microspheres of carbon and silicon carbide layers are robust and able to manage high temperatures. Cladding and fuel system structures are like those employed in other commercial reactors. Microreactors that use heat pipes have channels filled with nuclear fuel through large metallic blocks. The heat produced by fission in the fuel diffuses to the heat pipes and is transferred to the power-conversion system. The block, operating at very high temperatures, is under high thermal stress and potential creep limits. Heat-pipe reactors demand careful integration of the nuclear fuel and the reactor system as all reactors.

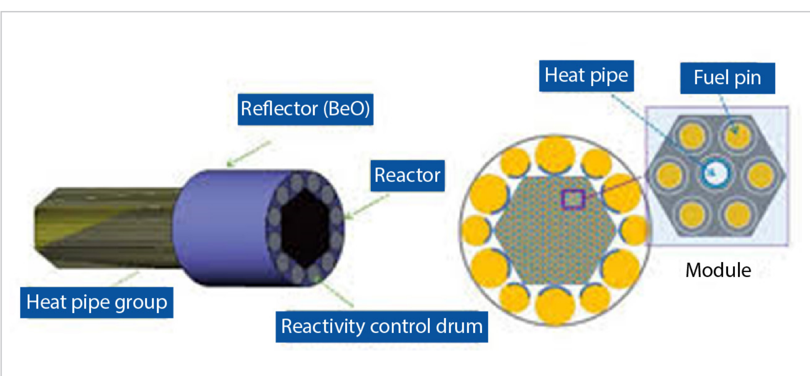

Figure 9. *Simplified microreactor fuel system.*

3 ADVANCED MANUFACTURING TECHNOLOGY, PROCESSES AND OVERVIEW

AMT could decrease costs, which would make nuclear energy more competitive with other energy production technologies [30]. Advanced manufacturing processes are often flexible, without the need for expensive, part-specific infrastructure, such as casting molds [31]. In addition to reduced equipment costs, this versatility can significantly reduce lead times and labor costs while shortening costly, forced reactor shutdowns for the reproduction of a part that failed [32][33]. Many advanced manufacturing techniques do not face the same challenges that conventional processes do and can simplify production and part design while maintaining or exceeding functional performance [34]. Continued technology development is required to realize the industrial benefits of nuclear AMT.

3.1 AMT FOCUS AREA CATEGORIZATION

AMT process categories for applications in the nuclear industry are determined based on stakeholder engagement, literature surveys, and subject-matter expert knowledge (Figure 10). Each category consists of a variety of manufacturing processes, and these manufacturing technologies are not necessarily unique to the nuclear industry; therefore, many process optimization and development results can be borrowed from other industries. However, a new category of processes, identified as hybrid-process technologies, is currently developed for very specialized nuclear applications. This often is referred to in the wider industry as a combination of additive and reductive (like machining) processes. However, in the nuclear context, it may be a specialized process for the handling of actinide materials or a totally new process. Often, these process developments are proprietary or classified. One example of a new patented process is the Additive Manufacturing as an Alternative Fabrication Technique process from INL [35].

Figure 10. *Graphical summary of the five main AMT categories for application in the nuclear industry.*

3.2 SUMMARY OF AVAILABLE AMT ROADMAPS FROM INDUSTRY

This section provides a summary extraction from a report by Mo and Bhattacharya [36] for the Advanced Materials and Manufacturing Technologies (AMMT) Program of Department of Energy (DOE)'s Office of Nuclear Energy. This report provides a summary of AMT roadmaps from the Nuclear Energy Institute (NEI) [37]; Electric Power Research Institute (EPRI) [38], America Makes [39], and NRC [40].

Laser powder bed fusion (LPBF), direct-energy deposition (DED), cold spray, electron beam welding, and powder metallurgy-hot isostatic pressing (PM-HIP) have been identified as of great interest to the nuclear industry by NEI, EPRI, and the industry. The focus of America Makes is on additive manufacturing; thus, the AMTs in common for all organizations are LPBF and DED. For different purposes, all organizations are in need of or interested in as fabricated (by AMTs) materials properties, including the properties after heat treatments, as well as the materials' performance data, such as resistance to fatigue or stress corrosion cracking and irradiation data [38]. For regulatory acceptance (by NRC AMT submittal review), quality data will be needed: e.g., material properties, mechanical properties, chemical composition, microstructure, fatigue resistance, fracture toughness, environment, component, and life cycle performance. The main conclusions from the summary report are listed below and presented in Table 2.

Feedstock quality control was considered to be a gap by EPRI, America Makes, and the NRC. America Makes indicated the research and development needs with respect to the reuse of powder during the build. Reuse of feedstock can introduce contaminates as the material is handled in the atmosphere. Processing the feedstock can also change the details of the shape and size distributions of the powder changing the properties in the process.

Nondestructive examination improvements and guidelines and in situ monitoring are considered gaps or in need of data by EPRI, the NRC, and America Makes. Monitoring surface contaminants like oxides, nitrides and oils could help sort out undesirable feedstock. Periodic or online measurements of flowability could address changes in size and shape.

NEI and the NRC indicate the need to compare advanced method of manufacturing (AMM) components with those fabricated by traditional manufacturing methods that have been approved in American Society of Mechanical Engineers (ASME) code, in terms of material properties (e.g., strength, ductility, fatigue resistance). More tests to complete such comparison would be needed. A sequence or roll up of testing will help define expectations for AMM processes. Different processes may result in different performance expectations than traditional manufacturing. Lowering the material performance expectations can increase the probability the component will function as expected.

Quality-assurance and requirements for the AMM process and products were emphasized in all organizations with different expectations. AMM materials will require different and potentially much more parameters to be tracked during production. Control of processes and using designs known to be producible would allow few parameters to be tracked.

Finally, NEI, EPRI and NRC all state the need for increased collaboration and engagement with the NRC, even during the early application of AMM in the nuclear industry. More workshops and meetings to coordinate the stakeholders and standards-developing-organization activities were emphasized by NEI, EPRI, and the NRC. NEI, the NRC, and America Makes also describe the need for workforce development, including training and education for AMM [36].

Table 2. *Summary of AMTs and materials identified to be important by NEI and EPRI [33].*

Identified AMTs in common for all organizations	Identified AMTs in common NEI, EPRI and NRC	Identified Manufacturing techniques by each organization
LPBF	Cold Spray	NEI
DED	Electron Beam Welding (Already Permitted by ASME Code Section III)	Binder Jetting
	PM-HIP (Code Case N-834)	Investment Casting
		Adaptive Feedback Welding
		Diode Laser Cladding
		Hybrid Laser Arc Welding
		Hybrid Laser-Gas Metal Arc Welding (GMAW)
		Laser Cladding Technology (LCT)
		Chemical Vapor Deposition (CVD)
		Laser Peening
		Physical Vapor Deposition (PVD)
		EPRI
		Diode Laser Cladding
		Hybrid Laser Arc Welding
		Friction stir additive

3.3 CURRENT APPLICATIONS

Traditional manufacturing techniques, such as turning, casting, heat treating, and welding, have matured over the twentieth century and are well understood and established processes. Toward the end of the century, digitization allowed automation of many of these processes, together with improved control and efficiency [41]. As this flurry of adaptation began to slow, more-novel processes began to develop that departed from the traditional approach to manufacturing. The development of these technologies has been accelerated by the global information sharing permitted by the Internet; now, many early technologies are ready, and promising technologies are under development [42][43]. Transitioning from the current known and adopted manufacturing processes that reliably produce safety-related components to a new manufacturing process will require greater understanding of the new process as well as its qualification [44][45]. AMTs have the potential to provide an option to move from large-scale statistical production controls to individual measurements, contributing to part acceptance using digital threads [46]. Developing these techniques will be a background technology needed across nuclear, high-temperature, and high-cost niche industries.

New technologies require successful demonstration before use, especially for high-performance and high-risk applications. Especially over the past decade, additive manufactured components have become increasingly common for these applications and have performed their functions well, often exceeding expectations and their traditionally manufactured predecessors' performance. As examples of successfully integrated additive manufacturing (AM) components with excellent performance and reliability increase, industries are willing to rely on AM more, and the impact of the technology grows. The following sections will discuss examples of AM components in different industries that are relevant to nuclear energy because of similarities in operating environment and/or risk.

3.3.1 AM LESSONS LEARNED FROM EXAMPLES IN AEROSPACE INDUSTRIES

The aerospace industry, both commercial and military, has embraced AM because of the geometric-design freedom and high-performance materials available (Table 3). Engineers can significantly reduce the mass of components while maintaining the necessary functional strength by producing complex, low-density lattice structures, as shown in Figure 11 These weight-optimization techniques are so popular that the industry has coined the denominal "light-weighting" for the technique [47]. Light weighting is an excellent application of AM that greatly increases efficiency, but it is not directly applicable to most nuclear energy applications. Special cases such like space-bound nuclear reactors could benefit from this application.

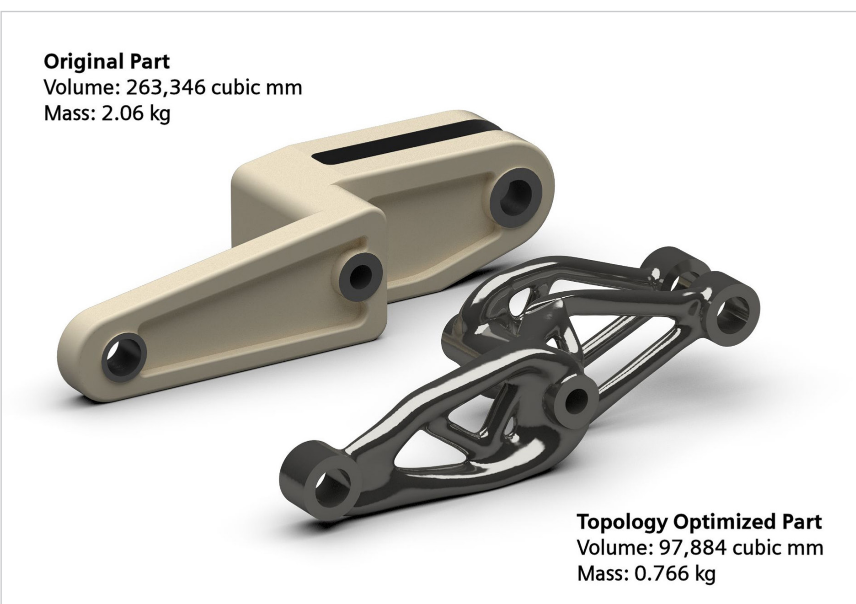

Figure 11. *Weight reduction of topology-optimized part produced by additive manufacturing by Siemens [48].*

Table 3. *Examples of AM applications in aerospace industries.*

Component	Application	Benefit	Technology	Material	Date
Siemens burner tips (1)	Repair of high temp/ corrosion environment burner tips for heavy-duty gas turbines	Successful repair of over 2000 burner tips with no faults reported while saving time (90% reduction), money, and requiring less of the original burner to be removed (20 mm instead of 120 mm).	Selective laser melting (SLM)	n/a	2013-present
Gas burner head (1)	Production of gas burner head for SGT-1000F gas turbine used in Brno, Czechia	50% reduction in lead time, 1600 hrs with no forced outages. First 3D printed burner component for heavy-duty gas turbine. AM burner head showed improved static mechanical and fatigue performance compared to standard cast part with better dimensional accuracy. Burner head has commercially operated for >12000 hrs with no failure indications.	SLM	Nickel based alloy	2016
Turbine fuel swirler (2)	Production of fuel swirler that have been installed in commercial reactors.	16 swirlers are produced at once in a print that lasts ~100hrs. Conventionally, the swirler requires ten machined and/or cast parts to be welded together in a process that takes ~6hrs per swirler excluding casting time.	Quad laser powder bed fusion (PBF)	Proprietary Inconel alloy	2013
Turbine blade (3)	Successful testing of AM produced turbine blades at 13k rpm, 1250C in SGT-400 turbine with 13MW capacity.	PBF turbine blades allowed advanced design to improve cooling which increases efficiency of turbine.	PBF	Proprietary Inconel alloy	2017
Link and fitting assembly (4)	Secures engine to MV-22 Osprey to wing.	Successfully tested and continued use without any noticeable difference from conventional part.	N/A	Ti alloys, plastics, steels, Al	2016
Fuel nozzle (5,6)	AM fuel nozzles for GE LEAP engines	30,000AM fuel nozzles are printed and used in LEAP engines around the world while combining 20 pieces that required welding into a single piece with 25% less weight while achieving >5x durability.	N/A	N/A	2018
Fuel nozzle (6)	AM fuel nozzle components for GE9X engines	AM processing simplified 900 parts to 16 printed components (in one case 300 to 1) that required welding/brazing to combine (casting attempts all failed). The parts weighed 40% less and cost 60% less and permitted use of Ti alloys that are hard to machine. Use of ceramic matrix composites (CMC) nozzles increased fuel efficiency by 10%. Parts performed well through 1800 dust/debris testing cycles.	Electron beam melting (EBM), PBF	Combo	2017
Turbine fuel swirler (2)	Production of fuel swirler that have been installed in commercial reactors.	16 swirlers are produced at once in a print that lasts ~100hrs. Conventionally, the swirler requires ten machined and/or cast parts to be welded together in a process that takes ~6hrs per swirler excluding casting time.	Quad laser PBF	Proprietary Inconel alloy	2013
Turbine blade (3)	Successful testing of AM produced turbine blades at 13k rpm, 1250C in SGT-400 turbine with 13MW capacity.	PBF turbine blades allowed advanced design to improve cooling which increases efficiency of turbine.	PBF	Proprietary Inconel alloy	2017
Link and fitting assembly (7)	Secures engine to MV-22 Osprey to wing.	Successfully tested and continued use without any noticeable difference from conventional part.	N/A	Ti alloys, plastics, steels, Al	2016
Fuel nozzle (5,6)	AM fuel nozzles for GE LEAP engines	30,000AM fuel nozzles are printed and used in LEAP engines around the world while combining 20 pieces that required welding into a single piece with 25% less weight while achieving >5x durability.	N/A	N/A	2018
Turbine blade (3)	Successful testing of AM produced turbine blades at 13k rpm, 1250C in SGT-400 turbine with 13MW capacity.	PBF turbine blades allowed advanced design to improve cooling which increases efficiency of turbine.	PBF	Proprietary Inconel alloy	2017
Link and fitting assembly (7)	Secures engine to MV-22 Osprey to wing.	Successfully tested and continued use without any noticeable difference from conventional part.	N/A	Ti alloys, plastics, steels, Al	2016

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In-core structural components can still benefit from topology-optimized design and structural lattices. Reducing the amount of material exposed to high neutron flux will reduce in-core absorption and can improve neutronic behavior while reducing the amount of hazardous waste at plant retirement. This is especially relevant for high-temperature advanced reactors, which will likely require nickel alloys for their high-temperature strength and creep and corrosion resistance but activate more than traditional steels.

Parts with total geometric freedom from AM can also help reduce fatigue failures. Structural lattices can be tuned to dampen vibrations from dynamic equipment or fluid forces. In 2016, a large beryllium reflector in the Advanced Test Reactor cracked. Engineering analysis hypothesized that the crack was due to irradiation induced swelling. [49]

AM can significantly simplify component assemblies, which traditionally require joining many geometrically simple parts by welding, riveting, or other methods to form a functional component. The geometric complexity permitted by AM, without additional cost, allows part production that combines these parts into a single, printed component, as seen in Figure 12. This saves time and cost by simplifying the production process while increasing strength, reducing weight, and reducing failure by eliminating joints in the assembly.

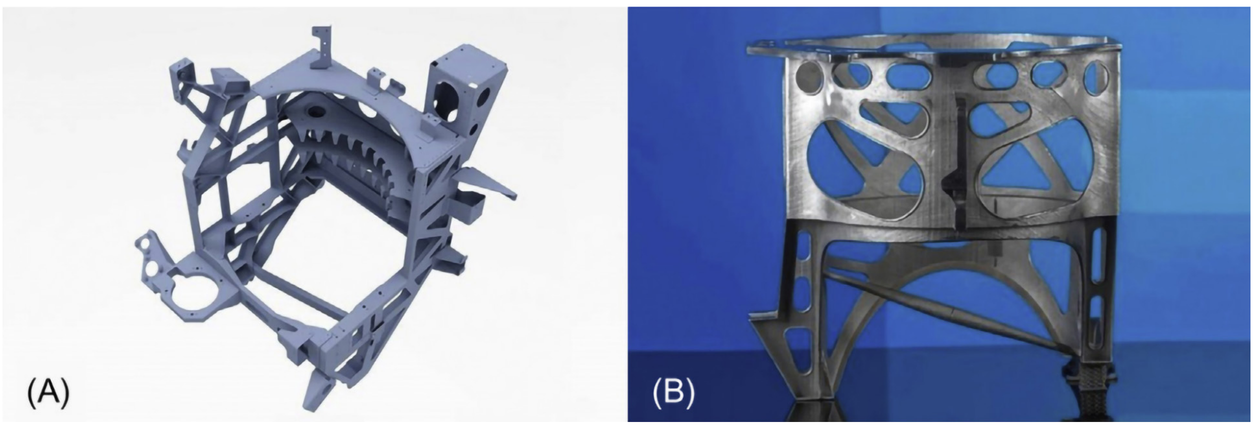

Figure 12. *(A) AM hydraulic reservoir rack from Airbus consolidating 126 parts. (B) Consolidated design into one part. Source: photo copyright Airbus, Hermann Jansen.*

3.3.2 AM LESSONS LEARNED FROM EXAMPLES IN NUCLEAR INDUSTRIES

Nuclear industry sector is considering AM, along with other advanced manufacturing methods for flexibility in component designs for power plants, reduce fabrication times, and condense cost [6][49]. AM is a new area of interest for nuclear energy; however, other methods, such as PM-HIP for nuclear energy components, are mature [9][6]. AM has the benefit of allowing constant process monitoring of each layer of material and has ability to engineer transition materials more flawlessly than established joining (e.g., welding, soldering, brazing) by minimizing heat-affected zones or to generate functionally graded material compositions [50]. Completely 3D-printed patterned grain sizes, composition distributions, and phase morphologies are conceivable by AM through optimizing the microstructure-properties relationships at the time of manufacture. This would permit better control and the collection of detailed information of manufacturing process concerning the properties of the final module [49].

Owing to the huge variations in temperatures, pressures, and radiation dosages, there is a need to use a variety of materials modifications in NPPs. AM technologies have been confirmed to generate graded compositions of variety of functional materials, for example, copper to steel, titanium alloys to steel, Inconel to steel, together with titanium alloys to carbides. [50]–[56]

Recently, a noteworthy amount of research in AMT is seen for nuclear instrumentation and sensor development for harsh environments using AM printing, especially for passive temperature and neutron-flux monitors, strain gauges, dosimetry, temperature transmitters, thermocouples, melt wires, ultrasonic thermometers, miniature fusion pocket chambers, etc. [9],[58]–[61]

The DOE's Office of Nuclear Energy (NE) finances research work in the area of advanced manufacturing and related technologies through the AMM initiative, under the Nuclear Energy Enabling Technologies (NEET) Program [59]62. The aim of the AMM initiative is to perform research that primes innovations in manufacturing technologies that decrease costs and time required to create new NPPs and to escalate the reliability of essential nuclear energy components. Additionally, many companies and national laboratories are working under DOE to shape AM-feasible for the nuclear industry, such as BWXT, Novatech, X-energy, and TerraPower [2]. The NRC sponsored a public conference on AM for reactor materials and components in 2017 and 2020 and invited governmental bodies, national laboratories, standards organizations, and over 20 companies [2]. Industry participants who expressed interest in pursuing AM for nuclear applications included General Electric (GE), Westinghouse, Novatech, NuScale, Rolls-Royce, NEI, and EPRI, and ranged in interest from LWRs to more advanced reactors such as small modular reactors (SMRs). In nuclear industries, various areas of importance for AM-fabricated components may be expanded to other areas of interest related to nuclear energy, outside of the plant itself: fuel design, reprocessing of spent fuels, or recycling of spent fuel for reuse in reactors. Table 4 delineates the role of AM in nuclear applications. In these cases, AMTs were employed to abridge manufacturing processes and lower the level of materials and human labor required.

Table 4. *Examples of AM applications in nuclear industries.*

Component	Application	Benefit	Technology	Material	Date
Impeller (1,2)	Impeller replacement for fire protection pump in (Krško, Slovenia) (no malfunction since commission)	Obsolete part could not be reproduced conventionally so was reverse engineered and 3D printed. First AM part used in a nuclear power plant "better than expected performance."	N/A	N/A	2017
Thimble plugging device (3)	A low/no risk part which limits bypass flow through absorber rod guide thimbles. Installed in Exelon Byron Unit 1 (IL, USA)	Proof of concept, "first in-reactor part."	Powder bed fusion	316L	2020
Channel fasteners (4)	Channel fastener brackets to attach fuel channel to BWR fuel assembly in Unit 2 at Browns Ferry Reactor (AL, USA)	Replaces costly conventional process. First parts with digital twin from AM process.	N/A	n/a	2021
Chemical and Volume Control System (CVCS) Letdown Control Valve (5,6)	PROTOTYPE of a CVCS safety valve which must withstand over 20MPa in a 3" diameter volume at 650C	Hybrid DED/CNC was used instead of PBF to produce part since it is 30kg and requires smooth internal channels. Achieved Class 1 performance allowing it to perform functions with high severity in case of failure.	Hybrid L-DED (DMLM) and 5-axis CNC. Parts produced in sections and then joined together.	316L	2021

Table 4. Examples of AM applications in nuclear industries.

Component	Application	Benefit	Technology	Material	Date
Control Elements (7)	Al flux control rods for High Flux Isotope Reactor	Produced robust control elements at roughly a tenth of the cost of traditional machining while strategically embedding neutron absorbers.	Ultrasonic AM	Aluminum alloy doped with Eu and Ta	2016
Impeller (8)	Molten salt pump impeller for Kairos small-scale prototype	Print was successful on first attempt, completed in < 1 day by ORNL. Much faster/cheaper than traditional mold/cast/finish/machining process. Digital twin supplied with part.	N/A	N/A	20/8/11
Heat Exchanger (9)	Compact, high pressure heat exchanger	AM permitted complex geometry of a heat exchanger to maximize heat transfer in a small footprint while minimizing pressure loss.	N/A	Proprietary Inconel alloy	19/4/16
TCR	Many AM components of structural, functional, and peripheral varieties	There is not a ton of technical data about the specific components yet.	N/A	N/A	N/A

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3.3.2.1 IN-REACTOR DEMONSTRATION ACTIVITIES CURRENTLY IMPLEMENTED

Testing is increasing at nuclear test reactors. Irradiation in a reactor allows an integrated nuclear environmental result. Direct in-reactor irradiations are performed by both academic and corporate partners.

Increasing experience will be needed to create sufficient understanding to expand testing applications of AM components in reactors. Increased understanding will also allow additional materials to be studied with charged-particle studies and in-reactor applications. The understanding of AM components will necessarily enable the possibility to increase in-core applications. Qualification of AM processes must be developed to allow practical applications and increase the understanding of new materials. To date, approximately four instances of AM components have been implemented in operating reactors. Each is discussed below.

Westinghouse Thimble Plugging Device Debris Component

Westinghouse deployed a thimble plugging device to Exelon's Byron Unit 1 in 2020 (see Figure 14). The device consists of both non-AM 304 stainless steel and AM 316L stainless steel fabricated using LPBF.

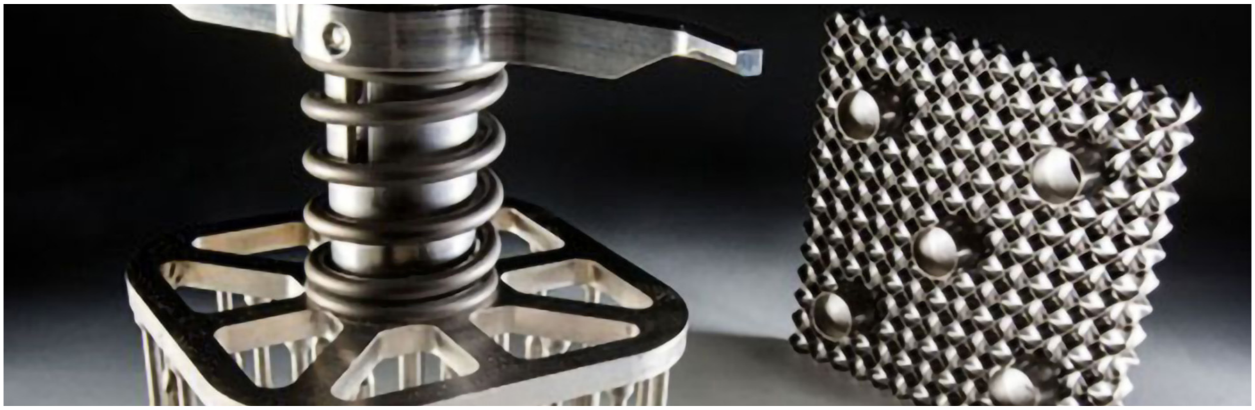

Figure 13. *Thimble plugging device developed by Westinghouse for Exelon's Byron Unit 1 [63][64][63]-[65].*

Fuel Assembly Channel Fasteners

The first safety-related demonstration of AM is fuel assembly channel fasteners that were deployed in Brown's Ferry, an NPP in Alabama. The parts were produced by Oak Ridge National Laboratory (ORNL), in partnership with Framatome and the Tennessee Valley Authority (TVA). A channel fastener is shown in Figure 14 Early in-reactor tests are being performed with AM components. ORNL has provided BWR fuel bundle assembly brackets to TVA for use in Browns Ferry-2 [63].

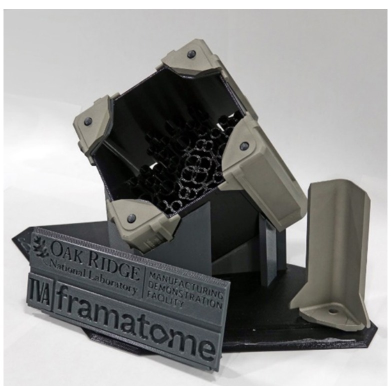

Figure 14. *Assembly channel fasteners developed for use in the Browns Ferry-2 reactor [63].*

Rolls-Royce and hot isostatic pressing body valves

Rolls-Royce uses many powder metallurgy components in its product range, most notably in aerospace and nuclear, the scope of which is likely to increase further in coming years. The following are in production on current PWR2 submarines [66].

1) Steam generator headers
2) Large bore pipework
3) Valve bodies (Metalska industrija Varaždin and non-return valves)
4) Pump components.

Figure 15. *Rolls-Royce AMT demonstration projects [66].*

Sulley et al. provide furthermore key insights for future applications for considerations and could benefit the nuclear industry for future applications:

> *It is desirable to eliminate large bore piping welds where possible and using the HIP process for single piece complex shapes can help to achieve this. However, this benefit can only be realized if the new shape is still machinable, or alternatively, if parts can be HIPed within required final dimensional tolerances [67]*

Impeller Fire Protection Pump

Siemens installed a metallic impeller for a water pump that is part of the fire protection system in the Krško nuclear plan in Slovenia. The 108 mm part was fabricated by 3D printing using SLM (Figure 16).

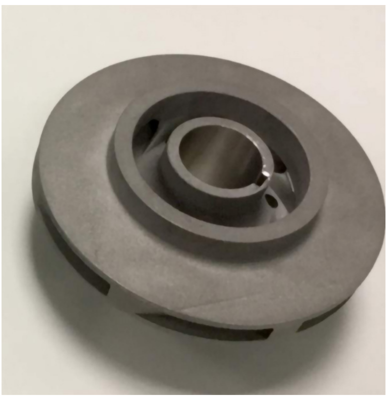

Figure 16. *Water pump impeller produced by Siemens for the Krško NPP [68].*

3.3.3 AM MATERIAL TESTING

The introduction of advanced-manufactured components to the nuclear energy industry is, necessarily, a complex series of steps leading to nuclear components with predictable service performance and lifetimes [69]. A critical step is demonstrating how AM component materials will perform in representative nuclear environments. Beyond complex chemistry, nuclear reactors operate in a high flux, mixed neutron and gamma-ray environment that uniquely damages materials. Great care is used in evaluating the performance of nuclear material [70]. Evaluating AM components' performance in radiation fields is also useful for space and fusion applications. Fusion materials for extreme environments are being developed with AM technology for first wall applications. The first wall in a fusion system has very high irradiation and performance requirements [71]. Space materials, even in directly nuclear applications, differ from terrestrial nuclear materials in that space-application materials tend to be for higher temperatures [72].

3.3.3.1 EVALUATING AM NUCLEAR MATERIALS

Materials created in AM processes are collectively reaching the stage of development where how the materials respond to radiation fields is important to furthering AM component use [2]. The effects of radiation on AM materials are evaluated by a range of studies. Components can be tested for chemical interactions separate from nuclear effects [73]. Additional exotic materials and fuels, only able to be manufactured using AM, are also being test fabricated to establish material properties [74][75].

ORNL's Transformational Challenge Reactor (TCR) develops materials to support advanced manufacturing for the new design of an HTGR [76]. This program is systematically testing samples of AM materials, some unique to HTGR reactors, to improve the design and deployment of a modern reactor [77].

Materials being studied include traditional 316L and 304 stainless steels [78]. Other materials required for advanced reactors are also being tested. AM-fabricated silicon carbide is being develop and tested for reactor applications [77][79]. Materials unique to AM technology, including high-entropy alloys, are also being developed and irradiated [80][81].

A unique application being developed is advanced instrumentation [82]. AM offers the opportunity to combine sensors, structures, and signal-carrying components into a combined structure. The benefits of AM offer unique opportunities for new reactor designs.

The transition to operating in the highly qualified nuclear industry requires demonstration of material behavior as it is exposed to neutron radiation fields. Typically, radiation exposure is performed in test reactors that are designed to produce high neutron radiation levels. The effects of neutron radiation on a material can also be simulated using protons and ions. Protons and ions more-easily produce material damage that approximates radiation damage produced over longer times by high-energy neutrons. Access to charged-particle accelerators is easier and more direct than access to nuclear test reactors. This makes charged-particle testing more applicable to initial testing of new materials. Typical nuclear structural materials, like 316L, are being extensively tested with charged-particle irradiation [83][84][85].

Testing of AM materials has continued to increase at nuclear reactors. Irradiation in a reactor can allow an integrated nuclear radiation, thermal and coolant conditions. Direct in-reactor irradiations are performed by both academic and corporate partners [86]. Research tends to focus on 316, but other materials are also being studied, including aluminum [87] and Inconel [88]. Post-irradiation results are being published indicating progress in AM maturity for nuclear energy [89]. Early in-reactor tests are being performed with AM components; for example, ORNL has provided BWR fuel bundle assembly brackets to TVA for use in Browns Ferry-2 [63].

Increasing experience will create sufficient understanding to allow testing applications of AM components in reactors. Increased understanding will also allow additional materials to be studied with charged-particle studies and in-reactor applications. The understanding of AM components will necessarily lead to increases in-core applications. Qualification of the AM processes will need to be increasing as our understanding of materials continues.

3.4 OPPORTUNITIES FOR AMT APPLICATIONS IN REACTORS

Many systems and components exist in very harsh environments. Advanced manufacturing, by potentially improving component performance, can potentially improve the reactor safety and costs by reducing the effects of the harsh environment. As AMTs are considered for different applications, they should be considered for the specific reactor because the environment and use of components may have different specifications. Design differences can change the optimum material and expected performance issues that most affect the reactor operation. Potential areas of opportunity for the application of AMTs are generalized below. These opportunities listed are not exhaustive and should also be considered with a business case and supply chain considerations:

The top and bottom plate in fuel bundles are complicated castings and multipart pieces welded together. The plates are complicated because of the large number of pins holding positions, need for structural integrity, lifting requirements, incorporation of flow filters and thermal-hydraulic efficiency. Using AM processes can reduce the parts count, allow more sophisticated foreign material filters and optimize mechanical performance. AM could address the complex required geometry, materials, and create the option for reduced machining steps. The need to protect delicate fuel pins from small particles in the reactor coolant that can create fretting failure has made effective filter designs critical to modern bundles. Advanced manufacturing could allow more complicated geometries that can trap particles without creating undo hydraulic flow resistance. These advanced filters could potentially build into the plate directly saving on parts count and fabrication.

Fuel pins can also potentially be improved with AM processes. The zirconium cladding in commercial plants can be a complex systems of alloy layers extruded into long thin wall tubes. The tubes are filled with finely manufactured and optimized fuel pellets creating the need for careful operation to avoid pellet-clad interactions. The gap between pellet and clad can also attract fission products complicating alloy chemistry and adds thermal resistance in the fuel system.

Fuel pins constructed with AM featuring material variation could create a system with optimized materials, clad, facing the coolant and continuously varied fuel material to optimize nuclear, thermal and chemical properties.

Actively changing the enrichment across the fuel would allow control of heat generation and temperatures. Poisons could vary across the pin and further control the fission rate across the pin and operating fuel cycle. Fuel fabricated with intentional voids can accommodate expected burnup for the fuel design. Variation can be made in both axial and longitudinal directions further improving options for improved designs. Elimination of the fuel-clad gap would simplify operational requirements.

The continuous variation of materials could also allow fuel pin systems that include additional ceramic materials, like SiC or ZrC, facing the coolant and separate fuel and clad inside the fuel. The segregation of materials with inert ceramics would allow separation of chemical systems allowing better clad, fuel, getter, and additive systems to be included.

Fuel channels, used in BWRs, can benefit from AM benefits. The use of continuous material variation would allow robust inert ceramic coatings and ductile structure. The capability of AM to introduce novel surface finishes and geometries can optimize the thermal-hydraulic properties. Improved materials, like SiC can apply to higher-temperature reactors or unique coolants as used in MSR.

Spacer grids are used along a fuel bundle to maintain geometry along the fuel bundle and improve flow through the bundle. The complex geometry, the need to include springs and minimize flow resistance make the spacers complex. AM could be used to improve the hot forming, local heat treatment and incremental forming. The use of lasers or multiple dice forming to create complex geometries could improve spacer fabrication and operation. Localized heat treating to create different properties in spring materials, contact surfaces and structures would be beneficial. At the extreme spacers or the preformed material could include multiple materials to optimize performance. Advanced joining with lasers and electron beam welding off potential benefits to spacer fabrication due to the small heat-affected zones.

These techniques have the expected challenges on process control, part acceptance and materials optimization. Beyond the production process development these applications are competing with series production of essentially the same component. Fuel pellets are an extreme example where thousands of parts are produced to the same mechanical specification. In this case traditional mass production techniques may always hold an economic benefit at the cost of less production flexibility. This limit applies to each application and would need individual optimization to produce the best overall component.

3.4.1 OPPORTUNITIES FOR AMT APPLICATIONS IN LWRS

The benefits of advanced manufacturing apply to both the current generation of LWRs and the next generation of advanced reactors. The required high-quality, well understood performance and limited production volumes make nuclear applications closely matched to AMT.

Across an LWR, well-established components can be improved with improved geometry; fuel bundle tie plates and heat exchanger components could benefit from AM. Improved design and fabrication options could improve performance by adding a tough or chemically inert coating to minimize stress corrosion cracking in nozzles and flow structures. Control of inhomogeneous composition within a structure could allow integrated instrumentation to better monitor component health. Gradient material control would allow advanced fuel and cladding designs with included coatings and fuel and poison distributions. Optimizing multiple layers of fuel and gradient cladding could provide optimal thermal and chemical performance.

LWR materials research center on 316 stainless steels, as demonstrated by research [90]. Other common current materials are Zircaloy alloys for cladding and uranium dioxide for fuel. The focus on accident tolerant fuels (ATFs) creates new materials and processes for LWR applications [91]. ATF includes SiC cladding, FeCrAl-alloy cladding, clad coatings, and fuel with additives to improve performance. These new ATF material applications provide an example of how new AMTs can enable new materials to be used in LWRs.

Recent work by Kumar et al provide a new technology of producing accident tolerant clad manufacturing process which was funded by the DOE-NE-AMM program. This cladding tube manufacturing process consists of a novel cold spray manufacturing technique and can also be applied to adding a coating to any clad or fuel system. This process may not be only relevant to LWR reactor systems and may be adaptable to other component and nuclear systems as well [92].

A variety of surface coatings may be considered for accident tolerant fuel concepts without changing the original design and dimensional aspect of the fuel cladding system. Advanced coatings of inert materials can reduce surface degradation that can lead to cracks, chemically assisted cracking. Suitably deployable coating systems can be used for component repair during fabrication and field repairs during plant outages. The advanced coatings would extend component lifetimes and reduced costs. Various nozzles, instrument tubes, grids and steam generators components could benefit.

Figure 17. AMT application in the Advanced Fuel Campaign as presented by Dr. Steve Hayes, 2019

3.4.2 OPPORTUNITIES FOR AMT APPLICATIONS IN LMRS

AMT has similar benefits for LMR as for LWR. Improved components with inherent material coatings, improved fabrication, and material choices will improve reactor safety and operations for a LMR. The use of advanced embedded instrumentation would particularly help with LMR maintenance and reactor maintenance. Improved instrumentation would help when working on the reactor under the surface of the opaque coolant. Inclusion of embedded heat tracing could improve plant operations. Fabrication of unique heat exchanges for the operating conditions of a LMR would help address high temperatures, pressure differences and corrosion.

3.4.3 OPPORTUNITIES FOR AMT APPLICATIONS IN MSRS

Again, improved components with inherent material coatings, improved fabrication, and material choices will improve component lifetimes, operations and potentially system performance of an MSR. Structural materials optimized for the MSR are particularly important. An open question exists for vessel lifetimes under irradiation, high temperatures and salt chemistry. Simplifying the conditions that the pressure vessel operates in will extend lifetimes and surveillance requirements. AM will enable better pumps and valves in the salt environment. Reduced part count and better serviceability are possible with AM. MSR heat exchangers are similar to LMR heat exchangers. They operate at high-temperature, large differences in pressure from coolant to secondary systems, and could suffer from corrosion issues. Better designs with better flow paths and strength would be an advantage of using AM in MSR applications.

3.4.4 OPPORTUNITIES FOR AMT APPLICATIONS IN HTGRS

HTGR have unique requirements because of the extreme conditions they can operate at. Carbon fabrication improved with AM would be a general benefit. Fabrication of refractory materials with improved geometry and part simplification would help with reactor design, operation and maintenance. High-temperature instrumentation fabricated from unique materials for high-temperature operation would be beneficial.

Silicon carbide is a material with many advantages for HTGR reactors. Having improved SiC fabrication would help with reactor operations, improved lifetimes, and simplified structures. SiC/SiC ceramic matrix composite materials would be particularly beneficial since they can be made into tougher structural components.

Improved high-temperature heat exchangers and high-performance He pumps are a direct application of AM components in a HTGR. Unique HTGR compacts made from nuclear grade carbon is an area of development. Being the core fuel/material, any improvements have benefits for the entire reactor design. [93][94][95]

3.4.5 OPPORTUNITIES FOR AMT APPLICATIONS IN MICROREACTORS

Micro reactor designs and applications envelope are ripe for the use of a variety of AMT processes, due to the effective use of topology optimization during design processes, possibilities to produce gradient materials and the unique features of processes to enable manufacturing of complex designs. All these attributes can result in a lightweight compact components and integrated manufacturing systems with embedded sensor technologies for autonomous operation. Table 5 show some examples of material challenges identified by the microreactor program where AMT processes can be utilized to mitigate the challenges.

Table 5. *Examples of material challenges identified by the microreactor program where AMT processes can be utilized to mitigate the challenges. [96]*

Monolith Material	Pros	Cons
Stainless Steel 316	Well proven and corrosion resistant	Neutron absorber, cannot handle temperatures > 600°C
Grade 91 Stainless Steel	Structurally preferred for reactors	Neutron absorber, not as well proven
Molybdenum	Operated >900°C	Neutron absorber
Aluminum Nitride (AlN)	Ceramic - slows neutrons down, decreasing fuel requirements	Structurally less stable than steel
Silicon or Zirconium Carbide (SiC, ZrC)	Ceramic - slows neutrons down, decreasing fuel requirements	Structurally less stable than steel
Graphite	Proven ceramic material, decreasing fuel requirements	Potential C migration to heat pipes

4 PROCESS CRITICAL CONSIDERATIONS: NON-DED MANUFACTURING PROCESS

AM is a relatively new technology in the nuclear industry and is quickly expanding and evolving. There are a number of developing technologies that may benefit nuclear energy that do not conform to the most commonly applied DED. These developing approaches to AM have many benefits, but many of these techniques bring an equal number of challenges that have not been solved because AM is such a new, complex field within nuclear. AM shows great potential to alter the nuclear supply chain and could reposition nuclear energy to the forefront of global energy technology.

4.1 AM: AN OVERVIEW OF NON-DED METHODS

AM encompasses many discrete technologies with countless subtle variants of similar techniques. The International Organization for Standardization (ISO) and ASTM International published ISO/ASTM 52900:2015 to organize the myriad of AM methods into seven main categories for use in this review. Table 6 lists existing AM technologies with two suggested additions to encompass several new techniques and focus more on the manufacturing parameters that influence the functional properties of the part. The promising AM categories, in Table 6, binder jet printing (BJT), Bound Material Printing and post build processing are discussed.

Table 6. *Major categories of AM technologies.*

ISO AM Category	Description	Materials	Subcategories
Material Jetting	AM process in which droplets of build material are selectively deposited	Polymers Resins Bio-inks	DOD PolyJet[a]
Mechanical Consolidation Deposition*	AM process in which mechanical forces bond material where deposited	Metals Polymers Metal Matrix Composites	Kinetic consolidation deposition Friction consolidation deposition Ultrasonic consolidation deposition
PBF	AM process in which thermal energy selectively fuses regions of a powder bed	Metals Ceramics Cermets Polymers	Selective laser sintering SLM Direct metal laser sintering EBM

Table 6. Major categories of AM technologies.

ISO AM Category	Description	Materials	Subcategories
Sheet Lamination	AM process in which sheets of material are bonded to form a part	Metals Paper Polymers Composites	Laminated object manufacturing Plastic sheet lamination Selective deposition lamination Laser foil printing Ultrasonic AM[b]
Vat Photopolymerization	AM process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization	Photopolymer resins	Stereolithography Digital light processing

* These categories are suggested additions to the ISO/ASTM list of process categories

a. TM, Objet, LTD.

b. TM, Fabrisonic

4.1.1 BINDER JETTING

BJT AM can produce parts quickly with a high degree of dimensional accuracy. A binder is selectively deposited in a powder bed to form a solid part in layers. Parts are then debinded and sintered to solidify the part, as seen in Figure 18. The binder can be deposited continuously (as in CIJ) or in droplets (DOD), but the process is primarily the same and the differences will be discussed where relevant.

To begin the BJT process, a roller or blade spreads an even layer of powder, tens of microns thick, over the print bed from a reserve powder bed or a hopper[97][98][99] [93][95]. After the binder has been deposited, the print bed is recoated in similar fashion and this process is repeated until the part is fully formed.

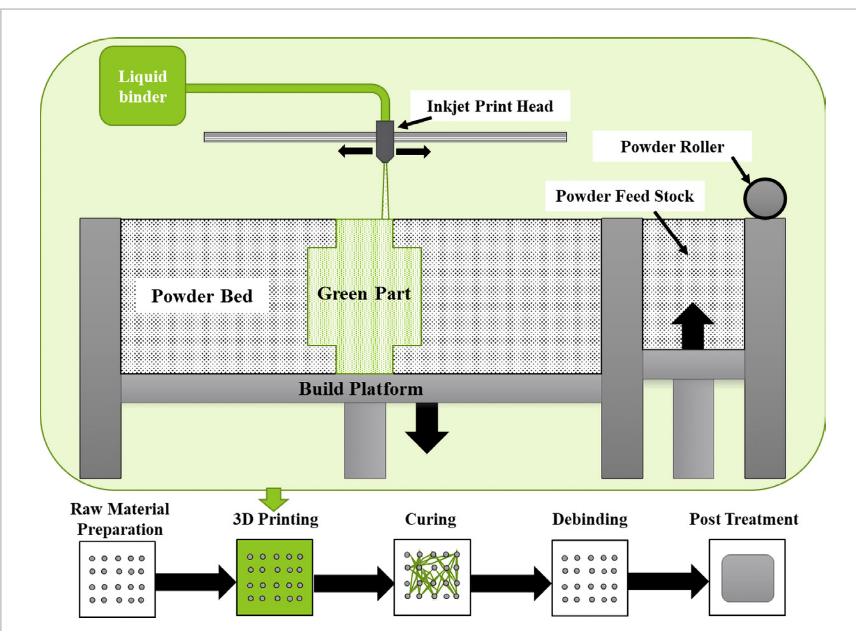

Figure 18. Materials processing steps of BJT.

The drawback of these established jetting processing methods is that they need wide efforts in terms of process planning or postprocessing to reach the final product with the anticipated geometry. These can be listed here:

(i). Binder jetting is a multistep process in which postprocessing steps (curing and densification) are required. (ii) As-printed parts show lower relative density (~50%) compared with the PBF AM processes, and densification from this state usually results in significant distortion of the geometry. (iii). Higher surface roughness and lower resolution are attained using binder jetting (0.5 to 50 µm) compared with some PBF AM processes. (iv)Development of post-processing strategies are still needed for most materials.[100]

Powder for BJT

Powder size and morphology are essential to produce high-quality, dense parts with good microstructure because of three main mechanics: powder flowability, packing density, and binder infiltration. Multiple sized particles such as 5 µm + 30 µm are sometimes used to accelerate binder penetration by increasing capillary action compared to monosized particles [96][101]. This combination also increases the packing density by allowing smaller particles fill the volumes between larger particles, as seen in Figure 19.

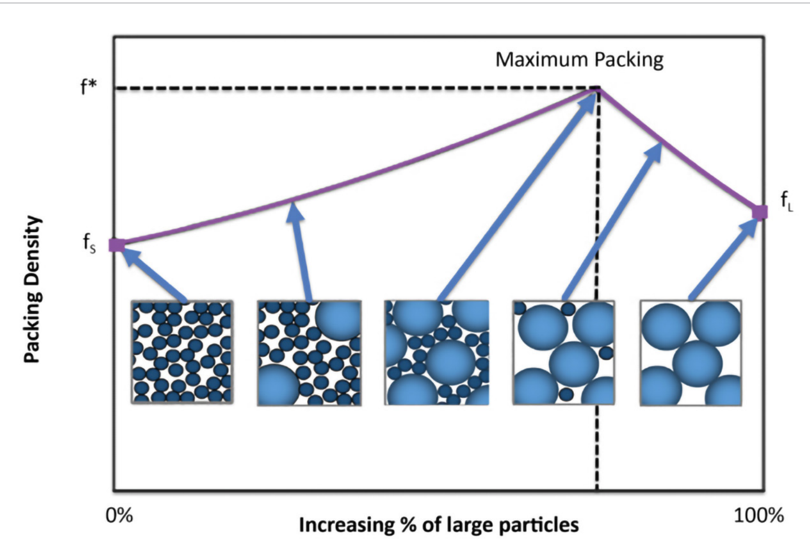

Figure 19. *A high packing density is associated with the production of high-quality, minimally flawed components and can be achieved using a powder with a relatively broad particle size distribution [101].*

Small particle sizes can increase packing density and accelerate binder infiltration, but as they become smaller inter-particle forces such as friction and van der Waals forces become more significant causing agglomeration and poor flowability [102]. Good flowability is essential to form consistent, dense powder packing and avoid major defects in the finished part. Spierings et al. define a flowability value (φ) which permits an analysis of powders to determine their flowability quantitatively which can help define critical maximum values that are compatible with various AM processes; for example, they define a maximum φ value of 2.5 for SLM [102].

Powders smaller than 5 µm are generally avoided for AM use because of unacceptable flowability and because of the increased danger of inhaling fine powders, but this can vary widely depending on the powder material, morphology, porosity, and AM process [101][102]. Binders with nanoparticles suspended in them can avoid this lower limit for particle size, thus improving density and strength of the finished part [100][101][103].

Smooth, spherical powders are ideal for powder-based AM because they help increase flowability, packing factor, and consistency, resulting in parts with better density, surface finish, and dimensional accuracy [103][104]. However, ideal powders are expensive to produce by methods such as plasma atomization the plasma rotating electrode, so most AM metal powders are produced by gas atomization which is a compromise between morphology and economics [102][104]. Common powder shapes are shown in Figure 20.

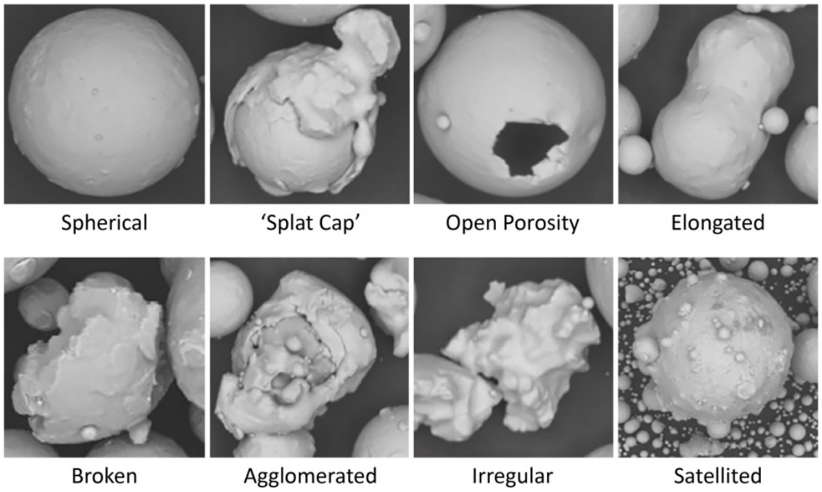

Figure 20. *Case study data from the National Centre for Additive Manufacturing, part of the UK's Manufacturing Technology Centre, details images of individual metal particles produced using gas atomization, illustrating the many different particle shapes which may result from the process [96].101*

Powder behavior is much more complex than particle size but quantifying the complex shapes of non-spherical particles does require simplification. Circularity, convexity, and elongation are three common descriptors shown in Table 7 that allow automated classification of particles based on two-dimensional profiles of the particles [81]. This permits a much-larger statistical sample which is more valuable overall than precise characterization of a few samples from other techniques such as the scanning electron microscopy (SEM) imaging shown in Figure 20. This technique provides quantitative metrics and statistical analysis of powders, which can strongly indicate how powders will perform in various steps of AM processes. This would allow effective and efficient regulation of AM powders to maximize the performance and consistency of powder-based AM parts.

Table 7. *Defining the three most used descriptors of particle shape (need citation) [101].*

Circularity is a measure of the closeness to a perfect circle. Circularity is sensitive to both changes in overall form and edge roughness.	Circularity = 1	Circularity = 0.64	Circularity = 0.89	Circularity = 0.67	Circularity = 0.50	Circularity = 0.35
Convexity is a measure of the edge roughness of a particle. Convexity is sensitive to changes is edge roughness but not overall form.	Convexity = 1	Convexity = 0.96	Convexity = 1	Convexity = 1	Convexity = 0.59	Convexity = 0.69
Elongation is a measure of the length-width relationship. Elongation is unaffected by edge roughness—a smooth ellipse has a similar elongation to a spiky ellipse of similar aspect ratio.	Elongation = 0	Elongation = 0.82	Elongation = 0	Elongation = 0.79	Elongation = 0.24	Elongation = 0.83

Binder in BJT

DOD technologies use multiple nozzles on a carriage head to enhance the complexity and acceleration of the part to be built. Multiple nozzles simultaneously deposit small droplets of a liquid binder into the powder bed; the binder quickly cures to produce consistently bonded powder in the deposition path. The binder droplet volume is small (10–80 pL) to ensure high geometric resolution [99][101]. Each droplet binds a volume of powder called a voxel (or sometimes a primitive) which slightly overlaps the adjacent voxels to bind them together. CIJ technologies work almost identically to

DOD, except that the binder jet is continuous, rather than periodic. This results in lower geometric resolution than DOD, and this makes CIJ is less popular, even though it reduces the risk of nozzle blockage [105].

The binder infiltrates both loose and bound powder by capillary action before it cures which can happen immediately or during a postprocessing step [96]. The binder viscosity and curing times are important parameters for this process, but they are much more consistent than other AM parameters; thus, they are not a major focus of research. After the binder deposition and powder recoating process is completed, the printed part is a "green body," held together by the glue-like binder. Green body parts are volumetrically 25–50% binder and air, which accounts for their delicate nature and the need for extensive postprocessing [98].

After the green body part is finished, loose powder is brushed or blown off the part before removing it from the printer. This can be done immediately because the parts do not need to cool, as some high-temperature AM processes require. Then the binder must be removed from the part to avoid contaminating the material.

The debinding process sometimes requires a chemical wash to dissolve the binder, but usually occurs by baking the green body until the solvent evaporates, usually between 200 and 600°C [99]. During the printing process, the binder need only infiltrate the powder on the order of micrometers, but once the part is complete, much of the binder can be trapped deep in the bulk material, centimeters away from a free surface. Green body parts cannot be heated too quickly without damaging the part and reducing density and strength, which limits the maximum binder removal rate to about 1 cm/hr; thus, large solid parts can require hours of binding time [99]. Once binder has been removed from the part, it is even more delicate than the green body and is referred to as a "brown body" or, sometimes, a preform, as shown in Figure 18. Sometimes pre-sintering is required to partially solidify the brown body so it can be handled and moved into the sintering furnace [106][107].

Postprocessing BJT Samples

Postprocessing to solidify BJT brown bodies may be the most-crucial step in the entire BJT process. Achieving dense brown bodies with low contamination and high geometric accuracy is essential to producing high-quality components, but it is the solidification process that determines the microstructure and properties of the final part. There are several ways to solidify BJT brown bodies, but sintering is the most-common technique, which may be followed by HIP and metal infiltration with a few other outlying techniques such as chemical vapor infiltration [108].

Sintering is process that allows mass transport between particles through diffusion by heating the material to accelerate diffusion. Sintering occurs at approximately 80% of the material's melting temperature to solidify and shrink the part, but several parameters dictate the process, which can affect the part differently depending on material, geometry, and brown body quality [99]. These are isothermal temperature, isothermal time, and heating rate.

Shrinkage during sintering is a good metric of sintering performance because it indicates how much the material has densified and how anisotropic the dimensional shrinkage is. Wang and Zhao performed a parametric study to compare the top three parameters shown above to determine their contributions to shrinkage [107]. This shows that sintering temperature is the most important parameter affecting brown body shrinkage and thus sintering quality. [107]

The heating ramp rate to change the isothermal temperature can impact the sintering process by increasing thermal strain. Thermal strain during the heat ramp increases exponentially after a critical temperature, approximately 1120°C for 316L SS, as seen in Figure 21 (a and b) [109]. The thermal strain increase continued into the isothermal part of the sintering process, which was higher for faster heating rates, as seen in Figure 21 (c and d). This research shows that heating the material very quickly and at very high temperatures can degrade the material and should be considered to produce consistent products. High heating ramp rates may also increase part deformation for complex geometry by introducing thermal gradients between thin and bulk features separate from the deformation that occurs from required sintering time.

The sintering atmosphere is a parameter that can be controlled but is often neglected. Any contamination in the material can affect the sintering process and reduce density and strength of the final part [49]. This is especially relevant for reactive metals and sometimes a low-pressure or an inert-gas atmosphere is used. Oxides are often already present in powders because of the very high surface area, and more contamination may be present from any leftover binder. Bai and Williams showed that using a reducing sintering atmosphere such as hydrogen can reduce /remove these oxides, increasing the sintered density of copper by more than 20% compared to a non-reducing atmosphere [110]. However, even with this improvement, the BJT copper only achieved an ultimate tensile strength 116.7 MPa compared to 200 MPa demonstrated previously with powder metallurgy or 318 MPa for wrought copper [110][111][112].

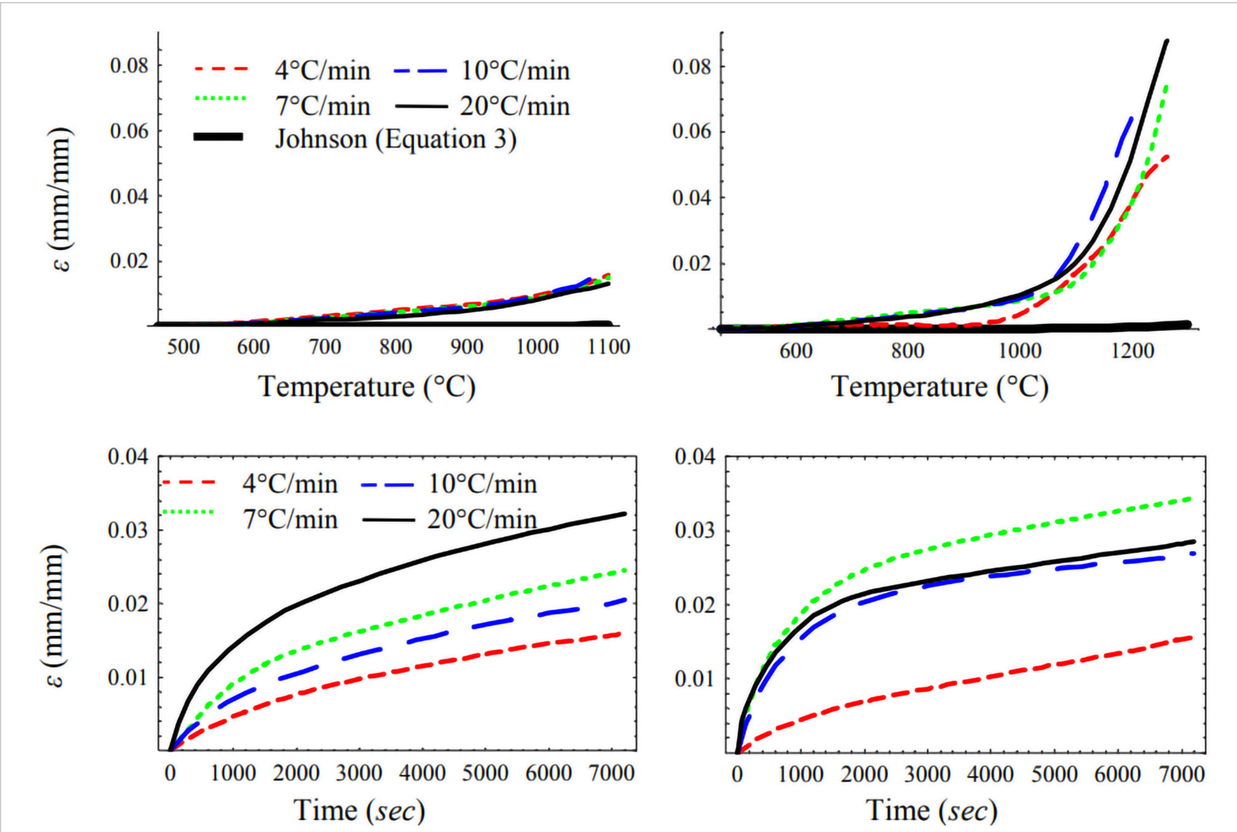

Figure 21. *Non-isothermal strain vs. temperature formed during the heating intervals before reaching isothermal peak temperatures (top left) 1100°C and (top right) 1263°C. Isothermal strain vs. time formed during the 2hrs hold at temperatures (bottom left) 1100°C and (bottom right) 1263°C [109].*

HIP as Post-Treatment Process of BJT Samples

HIP is similar to sintering in that it relies on high-temperature diffusion to increase density and improve microstructure, but the mechanisms and processes are quite different. The driving force for sintering is the reduction of energy in the material caused by defects such as grain boundaries, dislocations, and especially the surface energy from pores [113]. The high pressure in HIPing, usually argon between 100-200 MPa, adds an additional driving force which allows the densification to occur at a lower temperature than sintering which is important to avoid undesirable grain growth [112].

HIP forces any gases present in the pores to the surface or the high pressures cause the gas to dissolve into the matrix allowing the pore to collapse instead of into other pores as sintering does [109]. This results in a higher net density but can cause thermally induced porosity if the material is heated without pressure and the dissolved gases can achieve lower energy by forming bubbles [114]. Vacuum sintering before HIPing can reduce this effect [113]. Open porosity is not closed by HIPing because the high pressure gas works to expand the porosity instead of closing it. Sometimes the parts are encapsulated, but this is difficult for complex geometries and adds cost. If the part has closed porosity, this effect is not present, so HIP is expected to work best at densities above ~90% [115]. This is far from the ~50-75% density of debinded BJT parts and so HIP could be used as an additional postprocessing technique after pre sintering.

Infiltration as a Post-Fabrication Process

Infiltration involves injecting a BJT brown body with a low melting temperature infiltrate that fills open porosity via capillary action improving the density [115][116]. This technique is generally only used for metal BJT and with a different metal that has a significantly lower temperature, such as bronze in stainless steel. Material compatibility between the bulk material and infiltrant is important because the infiltrant must wet the bulk material so it can infiltrate small pores and also provide good functional properties to the finished part. [115] Homogeneous infiltration using a melting point depressant (MPD) in the infiltrating metal mixture can be used, but it is a difficult process because the MPD must have minimal impact on the functional properties of the final part [115]. Although metal infiltration does avoid the shrinking and warping that sintering brings, there are several problems that make it incompatible with nuclear environments. The infiltrant cannot fill closed porosity so the finished part retains ~10% porosity after infiltration and also has poor mechanical properties [108][116].

BJT Geometry

BJT has the capability of producing complex geometric features during the binding stage, but they must be compatible with postprocessing techniques that generally involve shrinking the part. This means that the part must be designed to shrink without cracking or warping into the final desired shape. Thin features will sinter much quicker than bulk ones causing them to shrink more rapidly which can cause high stress within the material causing it to crack, especially if the bulk feature is mostly still in the delicate, brown body state. Design for AM is a field that is growing and should be considered for all part production, especially AM processes like BJT that involve major dimensional changes.

BJT AM generally uses powder stock in the 4-45μm range which is finer than most AM categories. The BJT process is less dependent on particle size and shape than other AM technologies because the powder is bound rather than melted [104][115]. This makes BJT compatible with powders used by the metal-injection-molding industry, which exposes BJT to a wider range of materials with lower cost and a more established and dependable supply chain. Any material that can be sintered can be used to produce products using BJT, including metals, ceramics, and cermets are current materials suitable for nuclear applications. BJT is also used to produce sand-casting molds that can provide a cheaper alternative to cast low-production-volume metal parts.

The authors identified that BJT could also be used to produce nuclear graphite components. Nuclear graphite is used for neutron moderation, tritium sequestration, and structural applications. There has been little research on BJT graphite components, but it is theoretically possible, and recently published results indicate that BJT may be an effective, and even superior method of manufacturing dense graphite structures [117]. Advanced fluoride-salt cooled reactors could particularly benefit from high-quality, economical graphite structures.

One of the major characteristics of BJT is that it does not change the phase of the bulk material. This results in high deposition rates, currently up to 50 kg/hr [118], and low cost. Further, processing such delicate materials as ceramics and isotropic grain structures are possible because there is no directional thermal gradient. The absence of a thermal gradients or high mechanical forces result in low residual stresses that can warp parts or result in crack propagation. BJT can produce low surface roughness in the range of 6 Ra/μm and generally does not require support structure because of the bed of unbound powder. but sometimes complex parts will require support structure to minimize warping during the debinding and sintering stages when the part shrinks [104][116].

Extensive postprocessing is the major challenge that faces BJT. The debinding and solidification processes, such as sintering, HIP, or infiltration, impose additional costs and lead time. This also results in major shrinkage of the part, which can be accounted for using predictive software, but components may not achieve high dimensional accuracy if the parts are large, contain thin walls, or have varying feature sizes. The microstructure of BJT metals is usually worse than other traditional or AM methods and is characterized by high porosity, low strength, and low ductility.

Although BJT mechanical properties are worse than cast or wrought metals and many other AM methods, it can be similar to traditional metal-injection-molding parts [101]. The debinding process produces emissions that have not been sufficiently studied to understand possible health and environmental effects.

From the literature survey, it seems that BJT technology is appropriate for producing complex ceramic and cermet components but is not a promising technology for metallic parts. The gentle bonding process overcomes most of the challenges that face AM production of materials that can crack easily. However, metals that do not face the same challenges, do not benefit as much from this effect, and the lower mechanical strength compared to other AM processes disadvantage the metallic BJT components.

4.1.2 BOUND MATERIAL PRINTING

BMP, as a category of AM, is a useful addition to the list defined by ISO and ASTM, International. It varies from other categories in that the build material is interspersed in a temporary binding material before printing; this allows part printing using a variety of techniques available to the binding material, but unavailable to the build material. Although the subcategories of BMP are like existing AM categories, it is helpful to separate them by permanent build material for regulation-evaluation purposes because they rely on very different processing mechanics. For example, interlayer bonding may be the major factor affecting material extrusion (MEX) part performance, but sintering parameters may be the major factor affecting filament-bound material-deposition part performance, and sintering is a process that does not even occur in MEX AM.

Polymers and resins are compatible to a wide range of AM techniques that are often economical while maintaining high resolution. While these materials are incompatible with nuclear environments, binding a nuclear material, such as a ceramic, in the polymer or resin before printing permits the production of almost any sinterable material by any of these techniques. There are currently three ways of producing parts by BMP: filament bound material printing (FBMD), dispersed material lithography-based formation, and dispersed material jetting.

Figure 22. *316L stainless steel parts produced by FBMD [119].*

FBMD is based on MEX AM, which melts and extrudes a polymer filament when it passes through the heated deposition nozzle. FBMD filament is manufactured with the build material, generally a ceramic or metal powder, prebound in the two-part polymer [119]. Once the build is finished, the part must be debinded and sintered to solidify the metal or ceramic particles. FBMD parts show the regular ridges seen in MEX parts because the extruded layers are thicker than those seen in liquid- or powder-based technologies. However, the extra debinding and sintering steps shrink the entire part by about 17%, which reduces the ridge size also [120]. These ridges are visible in Figure 22, and may require postprocessing or machining to allow the parts to server their functional purpose.

The study by Zhang et al showed that the microstructure of FBMD parts has high porosity, with two scales of cavities. as seen in Figure 23. Cavities of 100-micron-scale, called L-voids, form because of gaps between layers, which form regular, square cavities when layer path orientation varies by 90 degrees [120]. Smaller, micron-scale cavities, called S-voids, form when the binder is removed from the part. The resulting porosity varies between 11 and 25% [119] which, combined with surface roughness that approaches near-net shape, makes FBMD a poor choice for structural nuclear material applications.

Lithography-based formation is based on vat photopolymerization AM and relies on curing a photopolymer resin that binds the dispersed build material particles into the net shape.

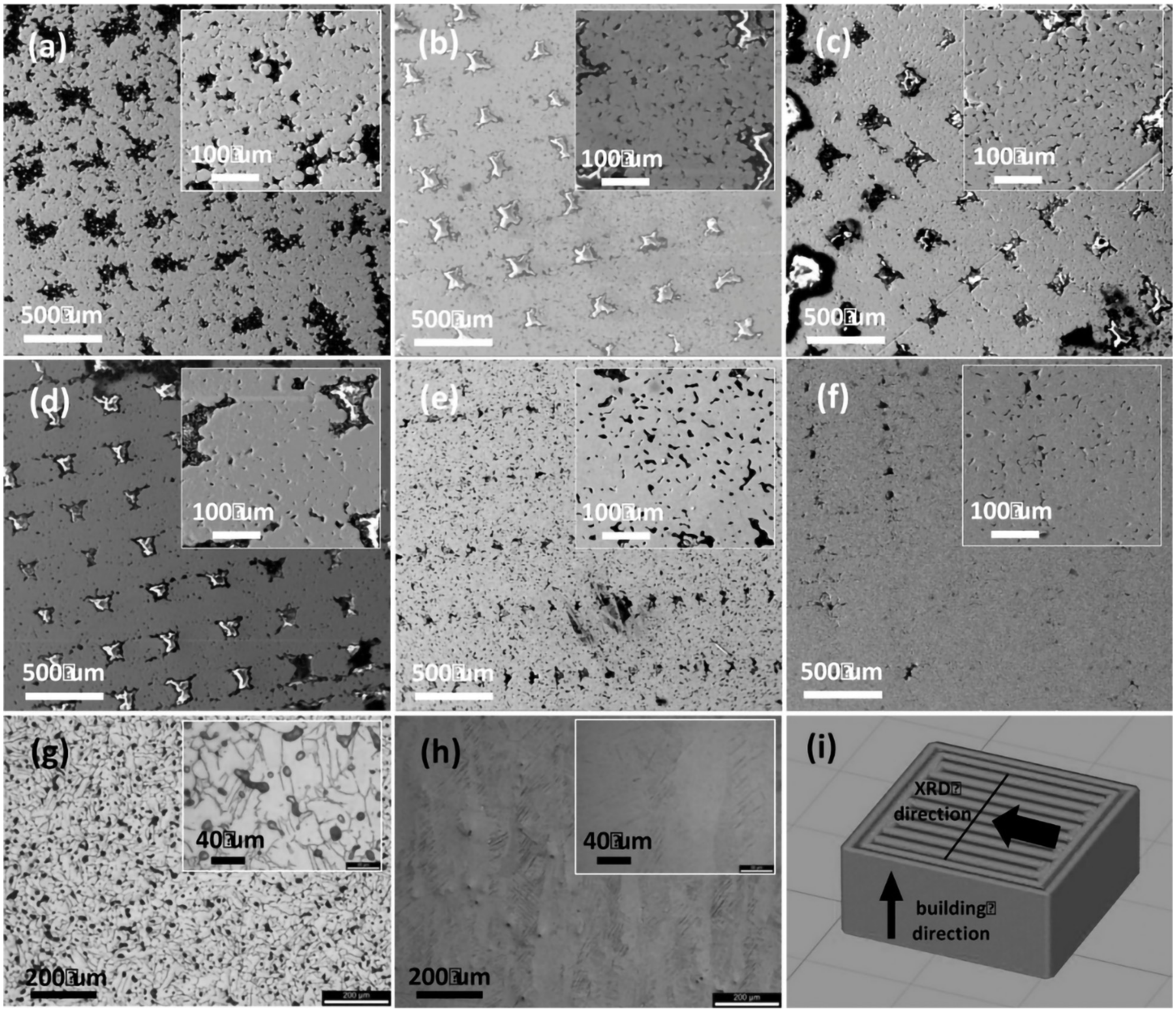

Figure 23. SEM images of Ti-6Al-4V samples sintered at different temperatures (a) 900 °C, (b) 1000 °C, (c) 1100 °C, (d) 1200 °C, (e) 1340 °C. (f) SLM manufactured Ti-6Al-4V sample. (g) Optical images of mFFF manufactured sample sintered at 1340 °C, (h) Optical images of SLM manufactured Ti-6Al-4V sample. (i) Illustration of the analyzed cross of mFFF samples [120].

4.1.3 ENHANCED POST-BUILD PROCESSING TECHNIQUES

Many AM techniques require postprocessing to produce functional parts. These are often heat treatment processes that can finish many parts in batches, as is done in sintering or annealing. Other postprocessing techniques—sintering, spark plasma sintering, hot isostatic pressing, and microwave sintering—are required to produce final part shapes from near net shape AM technologies, and some, such as debinding, are required for both.

AM part microstructure often has directional grains and high residual thermal stress from extreme temperature gradients, especially for techniques that rely on concentrated energy beams such as DED. These may be heterogeneous throughout the part because deposited material near the substrate or in thin-walled features can cool much faster than large sections of bulk material. There have been many experiments to improve microstructure, interlayer adhesion, and dimensional accuracy and to reduce thermal stress:

1) Interlayer rolling can be attached to wire and arc additive manufacturing (WAAM) processes to improve lamination and microstructure, reduce residual stress, and decrease porosity
2) Preheating the substrate reduces cracking and residual stress and improves wettability and bead geometry
3) Active interlayer cooling/heating can be added to WAAM processes to control microstructure, to improve finish and mechanical properties, and to enhance efficiency
4) Thermoelectric cooling can be added to WAAM processes to control bead geometry and reduce fabrication time by 60%, reduce internal stresses, and improve lamination, primarily for thin walls
5) Hot-wire measurement techniques can be used to measuring the effective thermal conductivity of layers (mostly ceramic coatings)

4.2 KEY FOCUS AREA: COATINGS AND SURFACE TECHNOLOGIES

Nuclear structural materials probably represent one of the most challenges, but opportunity-filled applications. Nuclear structural materials must withstand severe nominal and harsh operating environments. Moreover, they need necessary maintenance processes, special handling and decontamination operations, even after the end of operations or plant lifetime. An important objective in the nuclear industry is always to increase the component performance, and the development of new coatings materials and techniques creates the prospect of accomplishing these new designs and concepts.

Coatings protect surfaces of substrates, forming a barrier between the materials and its corrosive environment by virtue of their corrosion-inhibiting chemicals. To offer an acceptable protection option, the coating must be uniform, well-adhered, free of open pores, and self-healing for uses where there is a risk of physical damage to the coating [121].

Amorphous ceramic, metal and alloy coatings have been grown with exceptional corrosion resistance and neutron absorption capabilities [122]. These coatings, with further improvement, could be cost-effective options to enhance the corrosion resistance of drip shields and waste packaging, to limit nuclear criticality in canisters for the transportation, and to dispose of spent nuclear fuels. Iron-based amorphous metal designs with molybdenum, tungsten, and chromium have shown the corrosion resistance considered to be indispensable for such nuclear-related applications. Rare-earth-metal additions allow very low critical cooling rates to be realized. The presence of boron in these materials and their permanence at high neutron doses qualify them to work as highly efficient neutron absorbers for criticality control of nuclear instruments. These ceramic and amorphous metal materials have been manufactured as gas-atomized powders and used as nonporous, near fully dense coatings with the HVOF method for nuclear applications.

Several coating methods are available for applications in the high-temperature and nuclear industries: spray-coating processes, vapor deposition, and sputter-coating deposition processes. Additionally, diffusion coating, Ni-dispersion coating, electric arc-wire spray coating, electroplating, electroless plating, electrospinning, hot dipping, powder coating, ion implantation, anodizing, galvanizing, thin film vacuum coating, laser cladding, friction surfacing, and resistance seam-welding coatings are also important.

For instance, plasma spray techniques have been extensively used to fabricate ceramic coatings, due to their process flexibility and ease of application. They have the capability of depositing a wide range of coating materials onto various substrates. However, issues associated with plasma sprayings can lead to lower coating lifetimes, and they contain low bond strength with substrate, internal residual stresses, high porosity, and oxidation incorporated during fabrication process. On the other hand, techniques such as, CVD and laser-induced CVD (LCVD) have confirmed better control of microstructure. However, their low deposition rates make them less realistic for large-scale coating applications than the traditional plasma spray techniques.

The aim of this section is to critically review original and review articles, as well as perspectives, from foremost research in both academia and industry on all sides related to recent advances in design, processing and development of coatings and related technologies for nuclear applications.

4.2.1 THERMAL SPRAY COATINGS

The growth of thermal spraying techniques has played a key role in allowing new materials for functional smart coatings and substrates, thereby expanding the range of available possibilities. Thermal spray coating techniques include technologies on which metallic or nonmetallic materials coatings are placed through the same principle. The range of thermal spray coatings is shown in Figure 24.

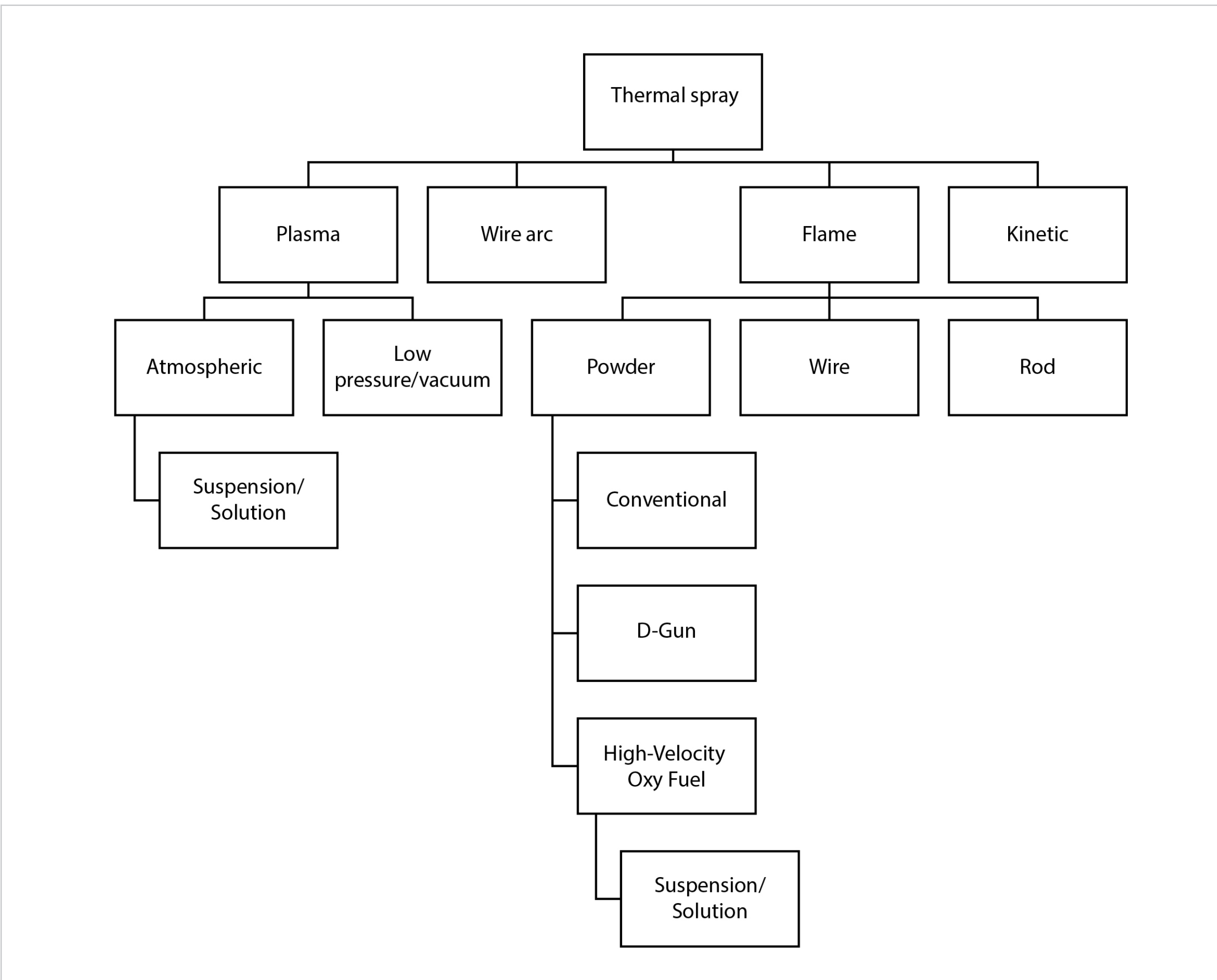

Figure 24. *Categorization of the thermal spray family of deposition methods [123].*

In this coating process, heat causes melting of the feedstock material, and a jet is extended to convey kinetic energy to the molten particles. They then coat the substrate surface and quickly cool to form a solid splash, simultaneously building up the needed coating [123]. A schematic diagram of the thermal spraying technique is shown in Figure

25. The flexibility on jet configurations and choice over thermal sources provides to a plethora of various coating processes, as can be seen in Figure 26, where each one yielding coatings with distinctive microstructures and physicochemical characteristics.

Figure 26 gives an impression of the physical conditions for some of some of the thermal spraying technologies described in this section.

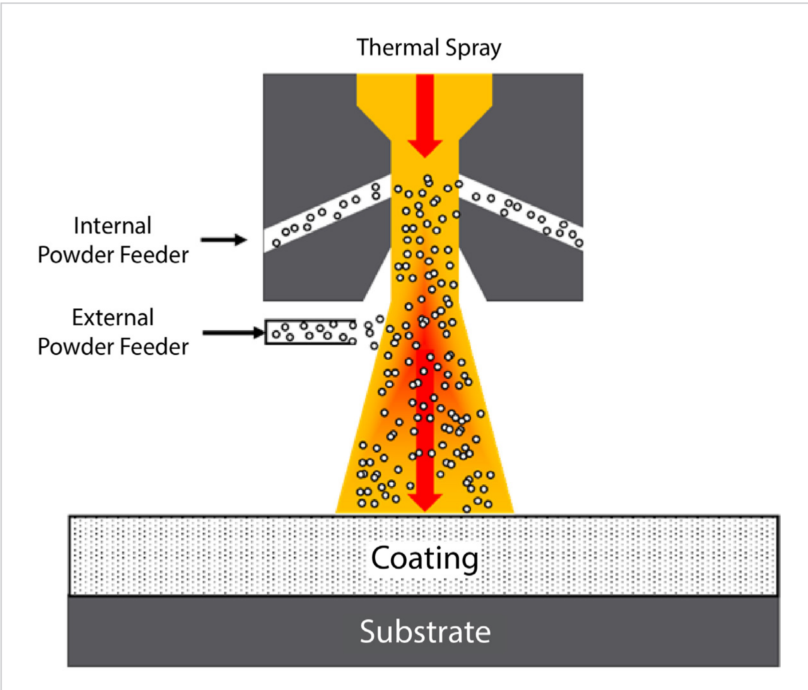

Figure 25. *Schematic presentation of a powder thermal spraying process with the two key components, a heat source and a jet.*

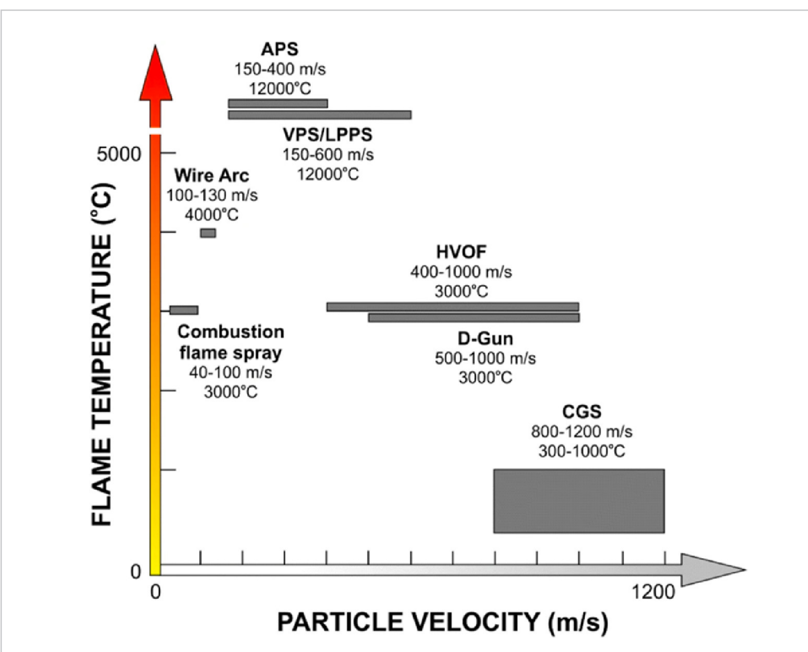

Figure 26. *Schematic of typical flame temperatures and particle velocities for atmospheric plasma spray (APS), vacuum/ low-pressure plasma spray, wire arc, conventional flame spray, high-velocity oxy-fuel (HVOF), detonation gun (D-gun), and cold gas spray [124].*

4.2.2 HIGH-VELOCITY OXY-FUEL COATING PROCESS

The thermal spray coatings shown in Figure 27 were prepared with the HVOF process, which includes a combustion flame and is characterized by gas and particle velocities that are 3 to 4 times higher the speed of sound.

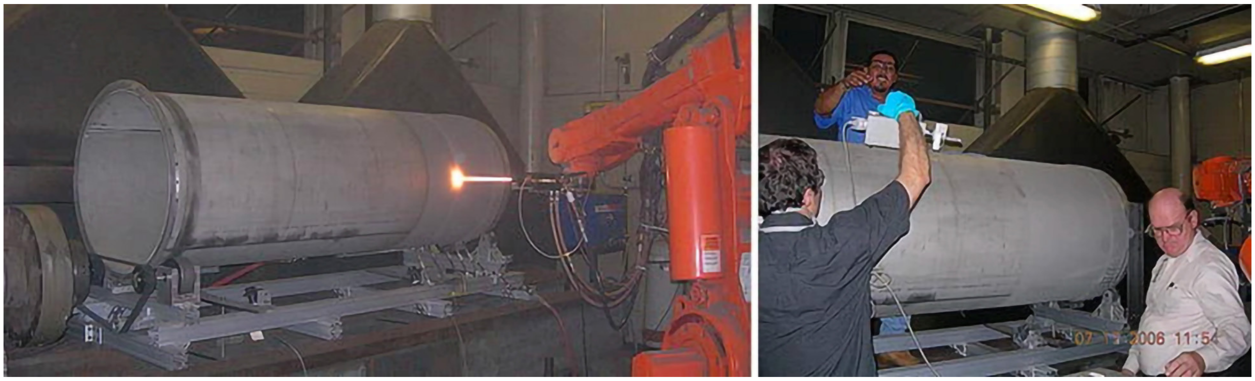

Figure 27. *HVOF process at Caterpillar extended to spray coat half-scale waste packages with SAM1651 amorphous metal. The torch is presented in the left frame, and the quality-assurance checks of the coating thickness and roughness are displayed in the right frame [122].*

4.2.3 PLASMA SPRAY COATINGS

Plasma spray coatings can be categorized into four major types: APS, low-pressure/vacuum plasma spraying, suspension plasma spraying (SPS), and suspension/solution precursor plasma spraying (SPPS).

The leading coating processes for yttria stabilized zirconia (YSZ) topcoats are APS and Electron Beam Physical Vapor Deposition (EB-PVD) [125]. The APS process uses thermal plasmas formed by a radiofrequency (RF) discharge, or direct current (DC) arc. This discharge lets flame temperatures reach 8000 K [126], and particle velocities reach roughly between 20 and 500 m/s, contingent on the distribution of particle sizes [127]. These high temperatures yield a high percentage of melted high-velocity particles, which then produce exceptional deposition densities, better bond strengths, and low porosity surface coatings as compared to thermal spraying techniques [123]. The achieved cost competency and better film quality obtained by exploiting APS processes have resulted in a rich implementation of these coatings for several industries.

Plasma spray in a controlled environment was invented in the late 1960s to cut the detrimental effects (e.g., oxidation) and unwanted impurities initiated in coatings due to in-flight heated particles interacting with their surroundings [123].

The APS technique is limited in terms of application for depositing small particles in the size range d10–100 µm, owing to the feedstock powder's inappropriate flowability for plasma spraying [128].

4.2.4 SUSPENSION-PLASMA SPRAYING AND SOLUTION PRECURSOR-PLASMA SPRAYING

To overcome these limitations, a wide range of solutions have been developed as an alternative for the traditional injection of powder feedstock. SPS and SPPS are most important among those [129]. The differentiation factor between these two techniques is shown in Figure 28. The key distinction between these two approaches is the precipitation of the in-flight deposited particles. These methods raise the flexibility of plasma spraying by exploiting smaller feedstock particle sizes and enabling deposited coatings with varied microstructures. This is the reason that advanced coatings for high-temperature by SPS and SPPS has been employed. This generally owes to fine porous structures and strain-tolerant columnar morphologies in both SPS and SPPS coatings; these ensure lower thermal conductivity than that of traditional APS or EB-PVD coatings.

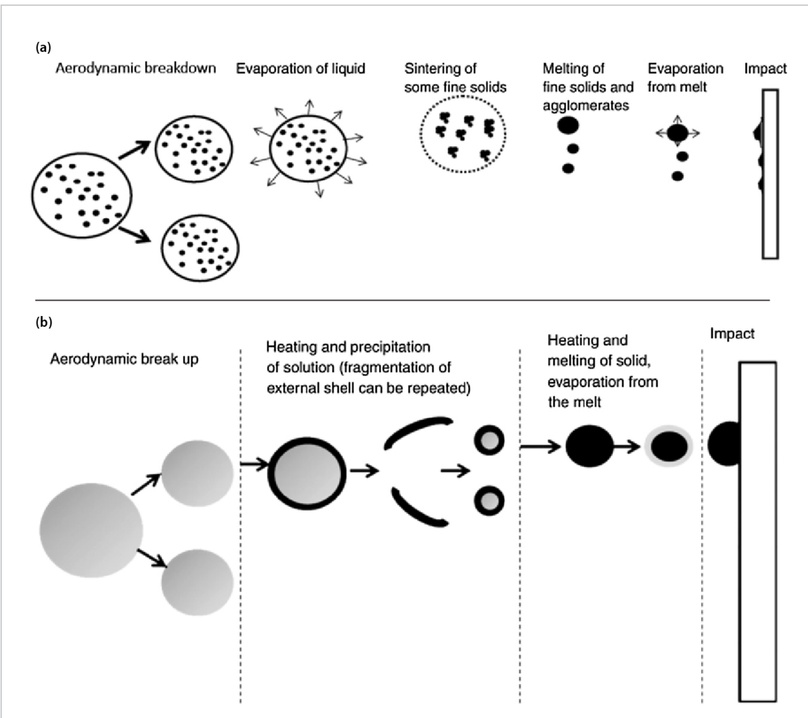

Figure 28. Deposition and particle conversion in-flight for (a) suspension thermal spraying and (b) solution precursor thermal spraying [130].

Despite of several advantages, plasma spray coating process produces porous ceramic coatings which tends to degrade in high temperatures and harsh environmental conditions. However, CVD methods can provide pure coatings of dense microstructures and better conformal coverage, although at a comparatively low rate. However, one recently recognized LCVD technique has proven to be both efficient and able to deliver a better deposition rate [131], which is similar to both the EB-PVD and plasma spraying techniques. The morphology attained by LCVD is porous, but owing to the nanoscopic pores in coatings, is suitable for decreasing thermal conductivity.

4.2.5 COLD SPRAY COATINGS

Cold spraying or kinetic spraying is based on the transmission of higher extents of kinetic energy into the feedstock particles to reach the anticipated bonding strength upon impact at the surface of the substrate. This compares with the typical use of heat transfer seen in other thermal spraying processes. It permits for the accumulation of ductile, deformable feedstock powder particles on the substrate without the need for any conventional melting, impact, and subsequent rapid solidification. This successfully reduces the in-flight particle oxidation and intrinsic residual stresses upon deposition [132]. The fundamental of this method is the use of pressured gases with reduced oxidation potential, such as helium or nitrogen. The gases are moderately heated up to 700°C, generally well below the melting point of the feedstock particles to intensify gas-flow velocities instead of heating the particles themselves [133]. The gas is guided through a de Laval nozzle once the required temperature and pressure are reached, which then achieve supersonic velocities (~1200 m/s) while dropping the gas temperature as the volume expands [134]. This lets the temperature to touch values below room temperature [135][136]. The subsequent sprayed coatings have the same phase as the powder feedstock without any oxide impurity and low porosity. The coatings show compressive residual stresses in its place for the usual tensile stress of other thermal spray processes and low ductility initiated by the broad work hardening involved in the deposition technique [132][135].

Another spraying approach is low-pressure cold spray (LPCS) which, as its name suggests, yields the accumulation of the feedstock particles at a lower pressure of carrier gas than is seen in either traditional cold spray or high pressure cold spray. The lower pressure needed in the LPCS gives some benefits—for example, smaller dimension and lower cost for the necessary equipment—causing it to be a very attractive option for convenient, handheld, portable coating method for onsite deposition or repairs [136]. However, low pressure associates lower particle velocity, which mostly disturbs the deposition efficiency of LPCS, being significantly lower than high pressure cold spraying process [137][138][139].

4.2.6 VAPOR DEPOSITION COATINGS

Vapor deposition is another important method for thin-coating fabrication. Apart from PVD, there are several vapor deposition methods available, such as vacuum deposition, sputtering, ion plating, CVD, medium-temperature CVD, etc. Advanced coating systems may include multilayer coatings and are often applied for protection from wear under complex loads and extreme environments [140][141][142].

4.2.6.1 PHYSICAL VAPOR DEPOSITION

Surface modification of material by PVD process is an efficient way of inhibiting wear and corrosion in automotive and high-temperature industries [143]. PVD is a vacuum-based thin (10^{-7}–10^{-4} m) film-deposition technique, mostly used for enhancing the optical, mechanical, and tribological properties of materials [141]. PVD has appealing characteristics for example greater hardness, better wear shielding, and low friction [144]. Due to the connection of the film characteristics to its morphology, the electrical, optical, and mechanical properties are contingent on the deposition angle [145]. Consequently, this angle dependent PVD technique, termed oblique angle deposition (OAD) [146], was expended intentionally to create self-organized nanostructures on substrate surfaces, as vertical deposition is very rarely achieved [147]. Figure 29 displays a schematic explanation of the OAD process. The incident vapor flux reaches at an angle θ at the substrate. The surface morphology of the deposited thin film is determined by the surface diffusion—a geometrical self-shadowing effect. The ability to manipulate morphology as well as porosity of films unlocks a huge window for applications. Optical coatings (as antireflective coatings or filters), biosensors, or catalytic layers are just a few examples of already established applications [146].

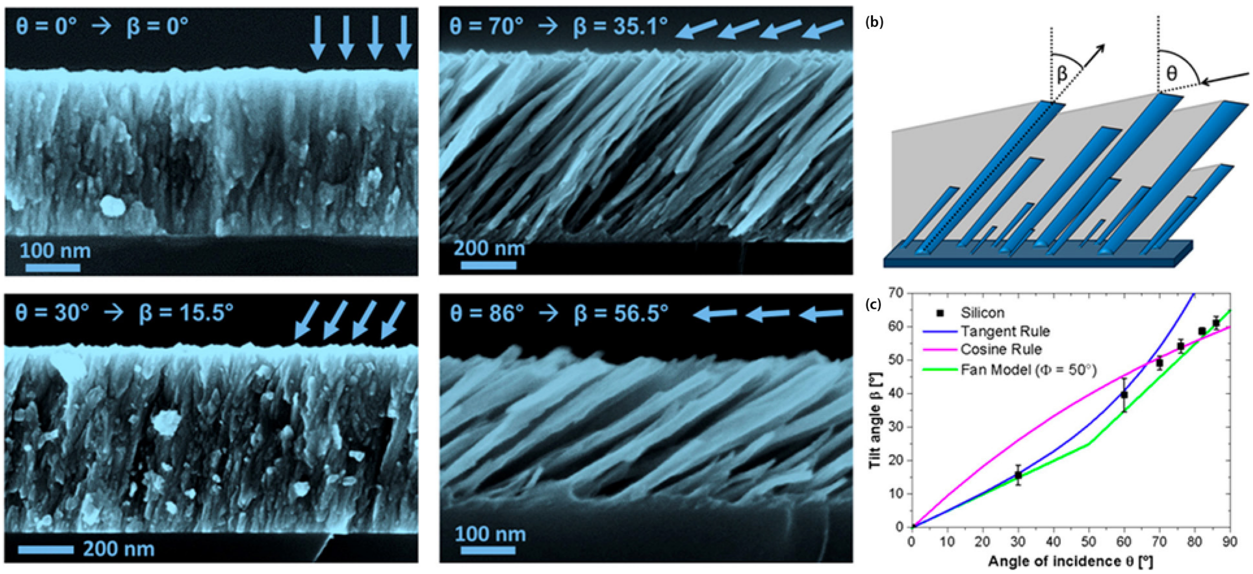

Figure 29. *(a) SEM cross-section micrograph of obliquely deposited molybdenum thin films, representing significant changes of the film morphology. The arrows designate the angle of incidence θ. (b) Oblique deposition with an angle of incidence θ hints to the formation of a columnar thin film, where the columns are noted by an angle β. The deposited film is porous owing to the self-shadowing effect as indicated. (c) The estimation of some common models for the tilt angles are shown [145].*

4.2.6.2 ELECTRON BEAM PVD

In electron beam physical vapor deposition (EB-PVD) technique, a target anode is bombarded by a high-energy electron beam created by a charged tungsten filament inside a high-vacuum chamber [146]. The high energized electron beam produces atoms from the target to translate into the gaseous phase. These atoms then precipitate into a solid thin coat form of the anode material, wrapping all in a vacuum. This is also called an "electron evaporation system" because the incident electron beam evaporates the source material and coats it on the surface of the substrate. Coating materials used in this technique include ceramics, metals such as titanium and zirconium, and aluminum-titanium nitride (TiAlN) alloy [148], and YSZ, which is the standard thermal barrier coating (TBC) for high-temperature application [145]. The thickness of the coating fabricated in this manner can range from 100 nm to a few micrometers and improves thermal and optical coating properties [146]. The foremost purposes of EB-PVD coatings lie in using TBCs for aerospace, energy-generation, automotive, nuclear, and marine high-temperature modules [147].

4.2.6.3 CHEMICAL VAPOR DEPOSITION

CVD is a process for fabrication of thin film coatings causing from the chemical reaction between a gaseous phase and the heated surface of a substrate [148]. CVD coating technologies are being used by various industries, such as tooling, electronics, aerospace, and fuel cogeneration. The electronics industry uses CVD to deposit semiconductor thin films while in the tooling industry, titanium nitride (TiN), titanium carbide (TiC), or aluminum oxide (Al_2O_3) are coated onto cutting or metal-forming tools. These hard coatings behave as thermal barriers and chemical-protection media between the workpiece and tools.

CVD replaces older, established methods for protecting components for the aerospace industries. In the space industry, CVD is expended to deposit aluminide or chromide coatings onto turbine blades, jet-engine parts, and other high-temperature components. These coatings increase the oxidation and corrosion resistance of the base metal. While the use of CVD coatings in the wider nuclear industry is relatively new, it is gaining increasing recognition [148] [149]. In addition to producing aluminides and chromides, CVD reactions can form coatings containing silicon, carbide, yttrium, hafnium, and other rare-earth refractory elements. In case of CVD, because the coatings are the outcome of the chemical reaction between high-purity gases and solids, coatings can be porosity and inclusions free. TRISO-type coated nuclear fuel particles, which have usually been used in the current HTGR, contains of a microspheric UO2 fuel kernel enclosed by four coated layers: a porous buffer pyrolytic carbon layer (buffer PyC), an internal dense pyrolytic carbon layer (IPyC), a silicon carbide layer (SiC) and an external dense pyrolytic carbon layer (OPyC). Fluidized bed (FB)-CVD techniques have been used for preparing the coated nuclear fuel particle, as can be seen in Figure 14 [149].

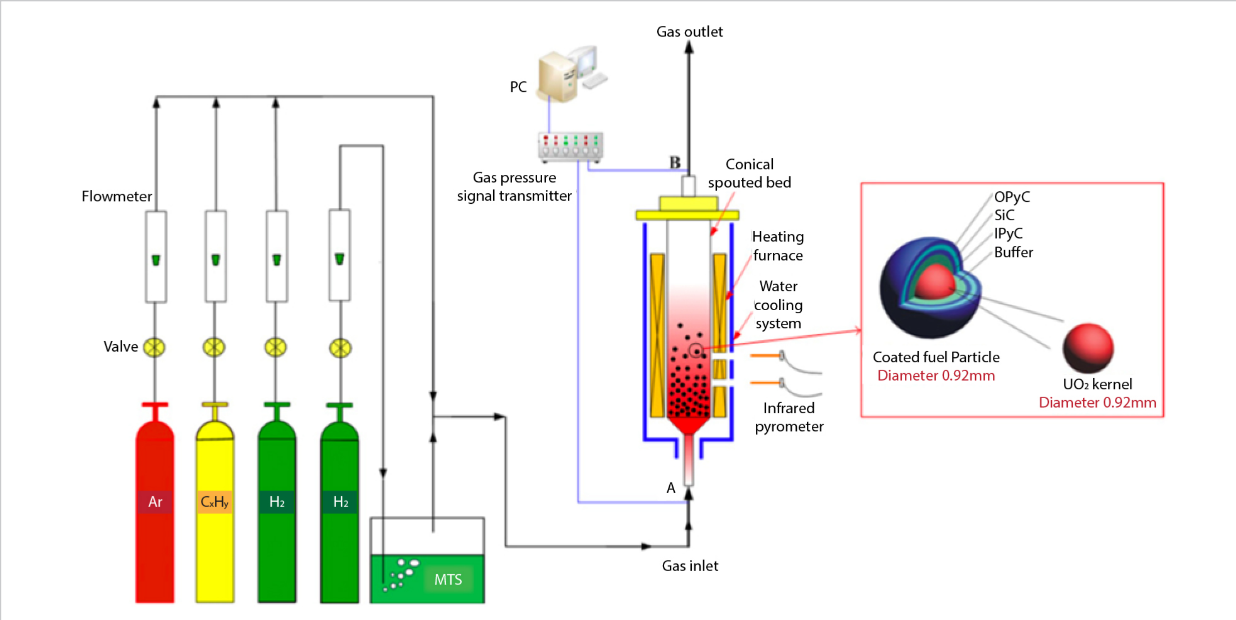

Figure 30. *Schematic illustration of the spouted bed coating system using FB-CVD [149].*

4.2.7 SPUTTERED COATINGS

The sputtering is a kinetically controlled surface-coating method in which the material sources or targets are made cathodic bombarded with inert-gas ions. Positive ions of inert gas (mostly argon) are established as a plasma that ignites between the anode (substrate) and target. Electrons are ejected from the cathodic region are rushed to the surface by the electric field and strike the surfaces of the target [140]. The kinetic energy is transported to the target atoms, which make a thin film on the substrate, as shown in Figure 31 [150]. Reactive gases such as nitrogen or oxygen are provided as supplementary to nitrides, metal oxides, argon, or numerous compound and multiple layers could be coated on desired substrate.

Recently, AM was coupled with sputtering and finding exciting applications. For example, microsputtering with integrated ion-drag focusing for AM of thin, narrow conductive lines has been demonstrated by Kornbluth et al. (the proposed architecture of the system is shown in Figure 32 [151]). A proof of concept demonstration of a continuously fed microplasma metal sputterer was demonstrated in which the microsputterer is capable of printing highly conductive lines, thinner than the width of the target, without the requirement of any postprocessing or lithographic patterning.

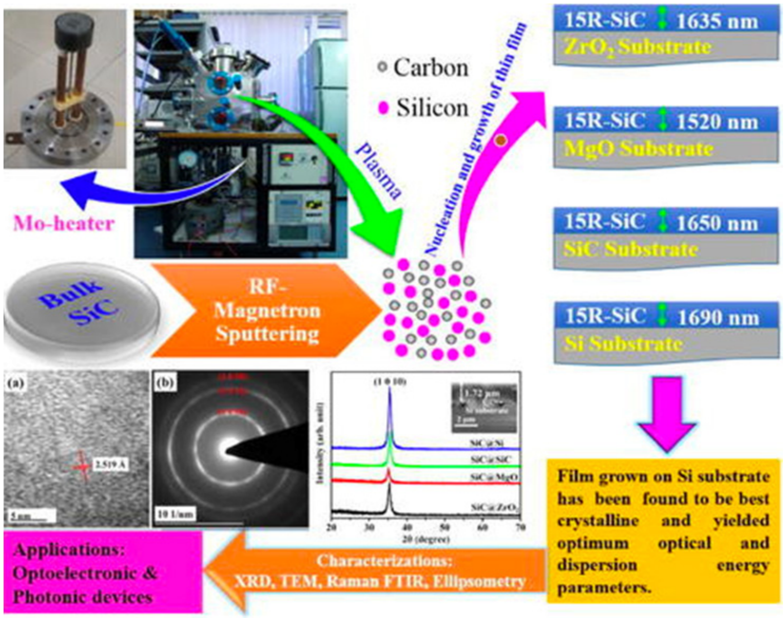

Figure 31. Schematic illustration of sputtering synthesis and characterization for 15R-SiC thin films on four different substrates [150].

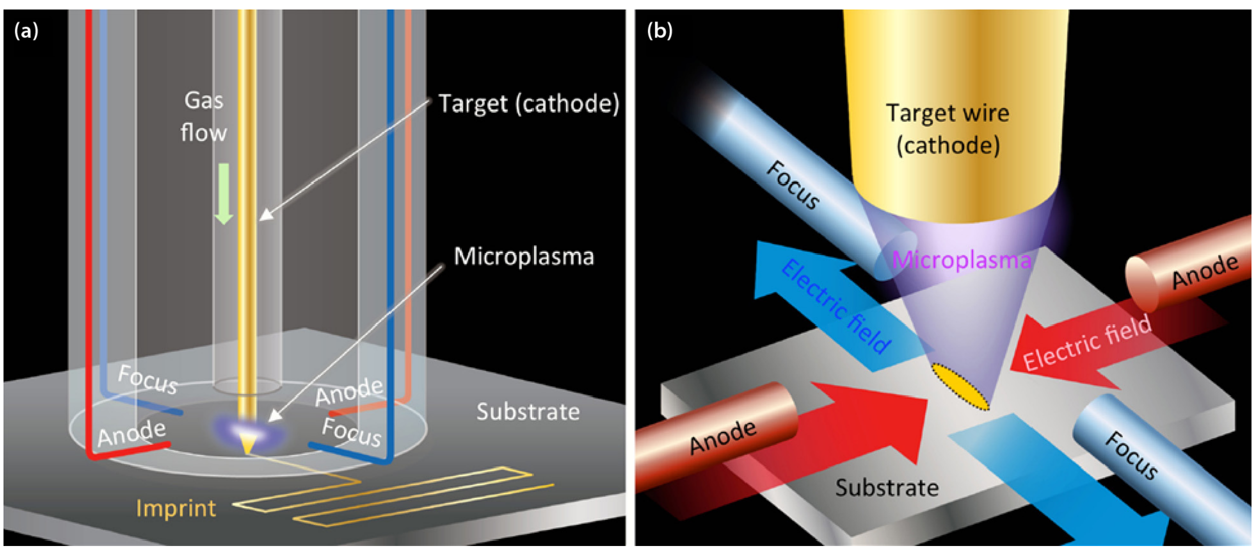

Figure 32. *(a) Representation of the printhead as a metal line is being deposited; (b) detail schematic of printhead tip exhibiting a focused imprint spot that is thinner in the direction between the anode electrodes [151].*

4.2.8 DED COATINGS

DED AM techniques are well fit for coating fabrication. Most recently, advanced coatings of various metal and alloys have been strongly considered using manufacturing techniques such as powder bed fusion, stereolithography, material jetting, and fused deposition modeling [152]. One challenge in designing surface coatings for high-temperature and nuclear components is the spallation of top coating under harsh thermal cycling conditions. Functionally graded material ceramic coatings can be considered to inhibit spallation and increase thermomechanical performance of coatings [153][154]. While not presently functional in industry, a few areas—for example, diffusion barrier coatings for high flux nuclear reactors, protective coatings for nuclear propulsion fuel elements and uranium fuels—could benefit from these advanced coatings and coating fabrication methods.

5 INFLUENCE OF USE OF AM COMPONENTS ON THERMAL HYDRAULIC AND NEUTRONICS PERFORMANCE

This section explores the potential benefits that AMTs can have on nuclear reactors' thermal hydraulics and neutronics performance. Thermal hydraulics in nuclear reactors have reached multiple limitations inherent to traditional manufacturing. These limitations are observed in existing thermal hydraulics system designs that, for the lack of manufacturing capabilities, produce operating requirements that can be difficult and costly to accommodate. The new generation of nuclear reactor design aims to tackle the underlying limitations of conventional manufacturing while improving system performance. AMTs provide a variety of innovative manufacturing options that are currently being explored to improve overall performances on the nuclear industry. This section focuses on possible thermal-hydraulic and neutronic improvements through AMTs and provides a pathway to resolve some issues in these areas using advanced manufacturing.

5.1 THERMAL HYDRAULICS SYSTEMS

The design objectives of thermal-hydraulic systems within the nuclear industry do not differ much from those seen in traditional power-generation industries. An estimate of the efficiency of a system is given by the Carnot efficiency:

$$\eta_{th}=1-T_{cold} / T_{hot} \quad (1)$$

which states that the efficiency will increase by lowering heat-sink temperatures (T_{cold}) and by increasing the energy-source temperatures (T_{hot}). Usually, heat sinks are condensers, recuperators, and other equipment that dissipates heat, and energy sources are within boilers or reactors. Thermal hydraulics' main objective is to optimize the overall efficiency of the system; in particular, the nuclear industry aims to efficiently transfer a nuclear fuel's energy toward the coolant or moderator. Details of how this is performed differ among the different types of nuclear reactors (see Section 2).

An efficient system should work under extreme conditions, subject to turbulent multiphase flows at extremely high flow rates and pressures, must be able to withstand large temperature gradients and mechanical and thermal stresses, and must withstand corrosive environments while operating non-stop for large periods of time and lasting more than 40 years with minimum maintenance.

Adding to the design challenges of such systems, nuclear thermal-hydraulic components must be able to operate in environments with high levels of radiation, where coolant conditions and neutron moderation are tightly coupled. The coupling between coolant conditions and neutronics requires a system flexible enough to avoid operational conditions in which instabilities are found. Furthermore, nuclear systems should not only be designed to avoid common and extreme thermal-hydraulic system accidents. Previous designs were based on traditional manufacturing techniques. New designs embody goals that require more ambitious material characteristics than traditional manufacturing techniques can provide in a cost-efficient way without hindering the operations.

This section summarizes the challenges to be addressed and matches them with AMTs that offer promise in those areas. Figure 33 presents a schematic of AM's impact on thermal hydraulics and neutronics in-reactor components.

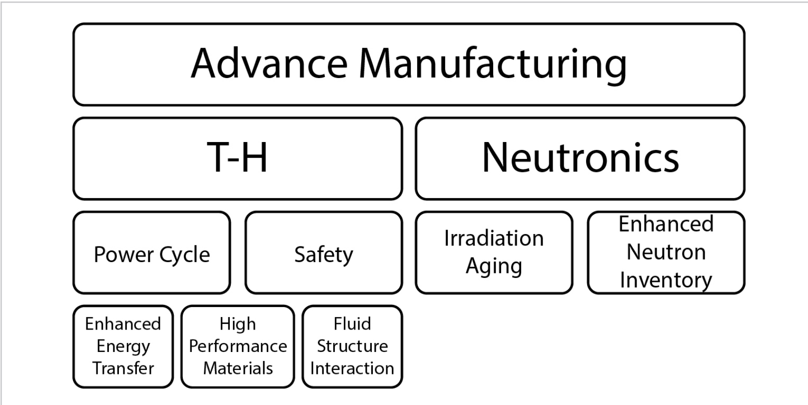

__Figure 33.__ Hierarchy of advanced manufacturing impact in thermal hydraulics (T-H) and neutronics.

5.2 THERMAL HYDRAULICS CHALLENGES IN THE NUCLEAR INDUSTRY

5.2.1 FLUID-STRUCTURE INTERACTIONS

Efforts toward power uprates had been possible through modifications of core components. For instance, fuel progressed from an 7 × 7 to a 12 × 12 BWR fuel assembly and 8 × 8 to a 17 × 17 PWR fuel assembly. These modifications require increased fluid velocities which amplify fluid-structure interactions. These interactions have been previously summarized [155] and include the following issues: crud-induced or corrosion power shift, CRUD-induced localized corrosion, grid-to-rod fretting failure, pellet-clad interaction, and fuel assembly distortion. These are some of the common issues found in the nuclear industry; if not addressed properly, expensive repairs to power-cycle components must be periodically performed.

Furthermore, the fuel design for uprates and new generation reactors depends upon an accurate prediction and characterization of pressure drop, flow distribution, and heat transfer. This is an area in which AM can play an important role. AM can be used for the design of reactor components with complex geometries to enhance turbulence and fluid mixing while reducing fluid/structure interactions. Thereby, it has been shown that drag-reducing manufactured artifacts can be designed without hindering heat transfer [156] These artifacts, or so-called riblets, help control and optimize the thermal turbulent boundary layer to create more efficient energy transfer systems. Figure 34 shows some riblets examples.

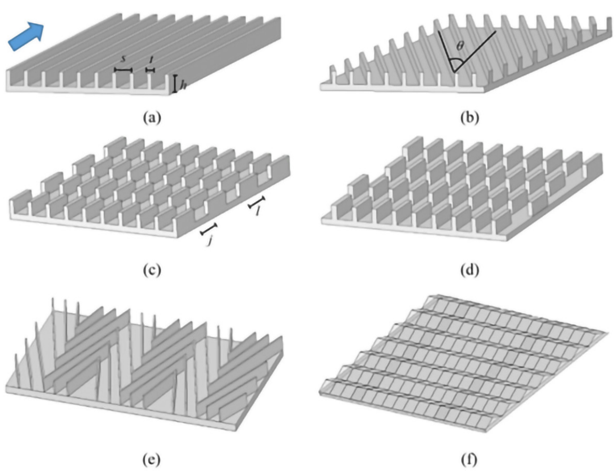

__Figure 34.__ Different types of riblets [156].

5.2.2 ENHANCED ENERGY TRANSFER

In nuclear reactors, the main energy transfer happens within the reactor core. Depending on the type of reactor, complex interactions between the fuel components and the coolant take place; for instance, in a BWR, the heat exchange happens mostly through boiling. This is one of the most-efficient means of energy transfer. However, boiling brings inherent challenges to reactors components that must be carefully addressed. In this section, these challenges are addressed, and possible solutions through advanced manufacturing are proposed.

5.2.2.1 ONSET OF NUCLEATE BOILING AND CRITICAL HEAT FLUX

The onset of nucleate boiling (ONB) and the critical heat flux (CHF) are two important parameters that require manufacture engineering optimization to better predict and control the overall reactors behavior. The ONB in a BWR represents surface and heating rate conditions through which phase change is promoted from liquid to vapor. ONB is related to the boiling length, which is the distance along the fuel length required to start boiling. This boiling length has direct implications for reactor criticality and stability. CHF is a thermal limit at which the nucleation site density becomes so large that localized dry-out regions on fuel surfaces manifest. CHF can cause undesired overheating of fuel elements and should be avoided by design. Both ONB and CHF depend on the momentum and heat transfer between a fluid and the fuel surface. Hence, AM is an ideal candidate to produce materials with surface optimization for the control and prediction of these boiling parameters. Surface modifications can be implemented to provide nuclear fuel with preferential boiling locations [157], [158]. Ideally, it is possible to have a fixed boiling length for multiple operational conditions that, in turn, can simplify the overall reactor design and operation. Multiple efforts have been developed to postpone CHF conditions by surface modification. One example is surface modification with nanotechnology [159] on which, to increase boiling heat transfer, surface roughness is increased by coating the surface with microstructures. This surface modification results in an increased number of nucleation sites. To avoid CHF, surface modification focuses on changing the wettability of the surface, rather than on the generation of nucleation sites. The aim is to reduce the contact angle such that the porous surface structure will extend the boiling regime and delay CHF [160]. An example of surface modification to improve boiling heat transfer can be seen in Figure 35. With AM, some surface areas of the fuel rod may be selectively modified to promote ONB, and other areas modified to delay CHF. Therefore, AM must be paired with computational, analytical tools to provide optimal selection of surfaces modification.

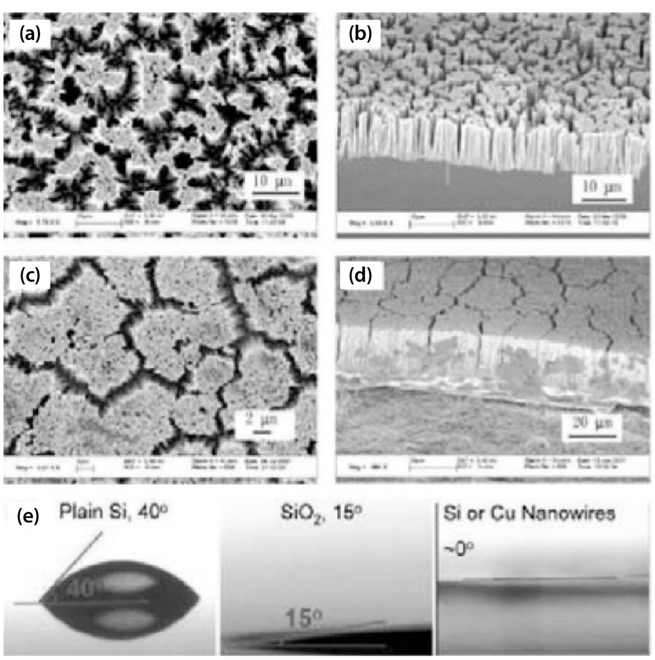

Figure 35. *Example of surface modification to change wettability [160].*

5.2.3 HIGH-PERFORMANCE MATERIALS

The desired power densities for new reactors designs and for uprates of operating reactors is possible through the inclusion of high-performance materials within the nuclear core. In particular, GEN IV advanced reactors pose great challenges for materials due to the high operating temperatures and radiation doses [161]. High-performance alloys—such as the 9Cr-1Mo steel, HT-9 steel, oxide dispersion strengthened alloys and high-entropy alloys—are great materials, capable of performing well even in harsh environments. During fabrication, the unique microstructure of these materials can be weakened by long thermal cycles of conventional manufacturing; therefore, researchers rely on AM techniques with shorter thermal cycles to produce them. Through AM, new high-performance structural alloys have been developed so as to overcome the challenges in these extreme service environments [162].

5.3 NEUTRONICS

5.3.1 TOPOLOGY OPTIMIZATION

The neutron inventory within a nuclear core is hindered by reactor components that are designed to serve solely as either containment or support. These components include cladding materials, channel boxes, grid spacers, fuel handling mechanisms. In traditional manufacturing, the added strength required by such components is compensated by thick material walls, which negatively affect fuel cycle economy. Reducing the amount of these materials within the core without adding risk to a component's critical functions has a positive effect on performance and creates cost savings [163] AM has been previously used in multiple industries to build high strength semi-hollow materials, minimizing their weight without hindering structural integrity and thereby saving material costs. For the nuclear industry, these components are also required to withstand the high thermomechanical stresses within a high-radiation environment. An example of topology optimization application was done previously with AM [76], and the resulting component structure is shown in Figure 36.

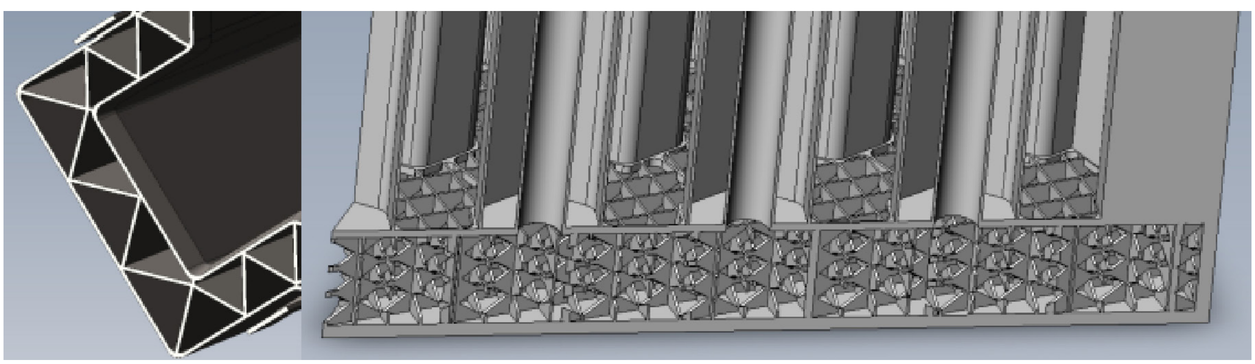

Figure 36. *Samples of structures minimalized to maintain performance and reduce material volume [76].*

5.3.2 GAP CONDUCTIVITY

A common feature in fuel rod design is a fuel cladding gap. This gap is designed to account for a fuel pellet's expansion under normal operating conditions. However, this gap can be viewed as resistant to energy transfer between the fuel pellets and the cladding, and in some scenarios, such as PWR conditions, this gap will generate temperature drops of about 100°C [76] between the fuel and the cladding. To reduce heat loss while maintaining a gap for fuel expansion, researchers used AM to design cladding with enhanced thermal conductivity. This was achieved by building spring-like structures on the surface of the cladding. These structures help reduce thermal resistance while keeping sufficient space for fuel expansion [163] Figure 37 shows an example of the design of these structures.

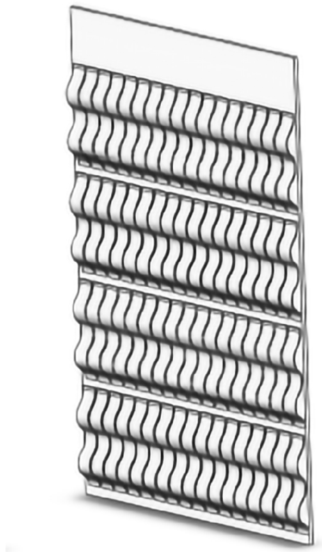

Figure 37. Spring-like structures [76].

5.4 SAFETY

During accident scenarios, the safety systems of nuclear reactors focus on the removal of the decay heat generated in the reactor core. Hence, multiple emergency core-cooling systems have been designed to efficiently quench decay heat. In new generations of nuclear reactors, these safety systems have seen a shift from active cooling to passive cooling. Regardless of the type of cooling system considered, similar energy enhancements provided by AMT can potentially improve performance. For instance, AM surface modification can be implemented, not only to enhance heat removal from the core, but also to enhance surface condensation on the decay-heat-sink component of the safety system. Further studies with complementary techniques are being explored, not only to modify solid material components but also their fluid counterparts. Enhancing the surface-fluid wettability can also be achieved through engineering heat removal by the fluid. An example of this approach is the use of nanofluids as a heat removal agent. Nanofluids have been explored previously as candidates to improve heat transfer in nuclear reactor systems [164], but they are inherently incompatible as a moderator for BWRs due to their pH. However, nanofluids are good candidates for the active or passive cooling required by safety systems [165]. Figure 38 shows how nanofluids achieve similar contact angles and wettability to the previously discussed surface modification through AM.

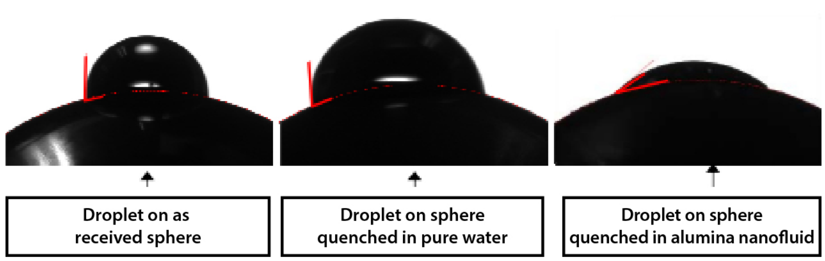

Figure 38. *Static contact angle of a water droplet on (a) an as-received clean steel sphere, (b) a steel sphere quenched in pure water, and (c) a steel sphere quenched in nanofluid. Low contact angles indicate high surface wettability [164].*

5.5 APPLICATIONS

AM is a candidate for the advancement of the nuclear industry as a competitive and reliable source of clean energy. AM allows the fabrication of engineered materials that satisfy the extreme demands of the nuclear industry. Although AM is still relatively new to the nuclear industry, it shows great potential given adequate development. Due to the fast-prototyping characteristics of AM, it can be used to further the research in thermal hydraulics. Multiple surface-liquid parameters can be controlled and tested to gain a better understanding of heat and momentum transfer in the near-surface region. This can have an impact in creating and improving correlations for the design of nuclear systems.

6 APPLICATIONS AND VALIDATION OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING FOR ADVANCED MANUFACTURING TECHNOLOGIES

The NEI reported that AMMs have the potential to transform the nuclear industry by producing high-quality components faster and less expensively while enhancing the performance of currently operating plants and advanced reactors. AMM could also be used to quickly supply replacement parts for obsolete components and to reduce warehouse inventories [37].

A survey of nuclear industry organizations identified 16 high-interest AMMs (Table 8) for manufacture of components for NPPs [37]. Nuclear industries are starting to investigate and adopt AMMs. Westinghouse has implemented powder bed fusion AM technologies in NPP components manufacturing and printed 316L stainless steel, Inconel 718, and Zr alloys as nuclear reactor components. Novatech and BWXT are working under DOE awards to support AM [2]. ORNL is leading efforts in the TCR, the key objective of which is to leverage AMTs to rapidly design and deploy a nuclear system on an accelerated timeline [163].

Table 8. *List of relevant AMM to NPPs [37].*

Additive Manufacturing	Near Net Shape Manufacturing
Powder Bed	PM-HIP
Directed Energy Deposition	Investment Casting
Binder Jetting	
Surface Modification/Coating	**Joining/Cladding**
CVD	Adaptive Feedback Welding
Cold Spray Additive Manufacturing	Diode Laser Cladding
Laser Peening	Electron Beam Welding with High PWHT
Physical Vapor Deposition	Friction Stir Welding
	Hybrid Laser Arc Welding
	Hybrid Laser-GMAW
	Laser Cladding Technology

Advanced manufacturing creates unique challenges for material properties compared to conventional manufacturing. The microstructure and mechanical properties are dependent on processing parameters of the AMT. For example, AM process parameters include the power level and speed of the heat source, power density, feedstock geometry, delivery method, and scanning pattern. Parameter selection affects the shape and size of the molten pool and the resulting thermal cycles, cooling rates, temperature gradients and solidification rates that, in turn, determine the evolution of microstructure, defects, and properties [166].

However, control of the microstructure, defects, and properties is challenging because of the need to collect large amounts of data to explore the parameter space. Mechanistic models that contain physics aid in connecting the process-structure property-performance (PSPP) linkage. Mechanistic models that cover multiple length and time scales are being developed to link process parameters to microstructure. Nicolas et al. have provided a survey of modeling and simulation techniques for advanced manufacturing technologies where they discuss the current state of modeling technology and discusses gaps for evaluating modeling and simulation methods for AMT [167]. One challenge is that large development efforts are needed to link processing parameters to microstructure through mechanistic modeling. Machine learning can supplement or replace mechanistic models in certain applications to accelerate the learning from processing parameters to microstructure. Machine learning has demonstrated its ability to perform complex pattern recognition and regression analysis without an explicit need to construct and solve the underlying mechanistic models. A digital twin of an advanced manufacturing process comprises mechanistic modeling, control, and machine learning to create a virtual replica. Machine learning can also facilitate each step of the PSPP linkage. Figure 39 shows the interaction between the PSPP linkage and the manufacturing digital twin; it highlights how machine learning impacts each step in the manufacturing process. Digital twins aid both the design and manufacturing processes.

Advanced manufacturing is embracing machine learning, and nuclear is embracing advanced manufacturing. However, very little research has been reported for a combination of advanced manufacturing, machine learning, and nuclear [173]. As machine learning has more success with advanced manufacturing, it will naturally be applied to nuclear applications. The remainder of this section will discuss the benefits and challenges with incorporating machine learning into AMT for nuclear applications.

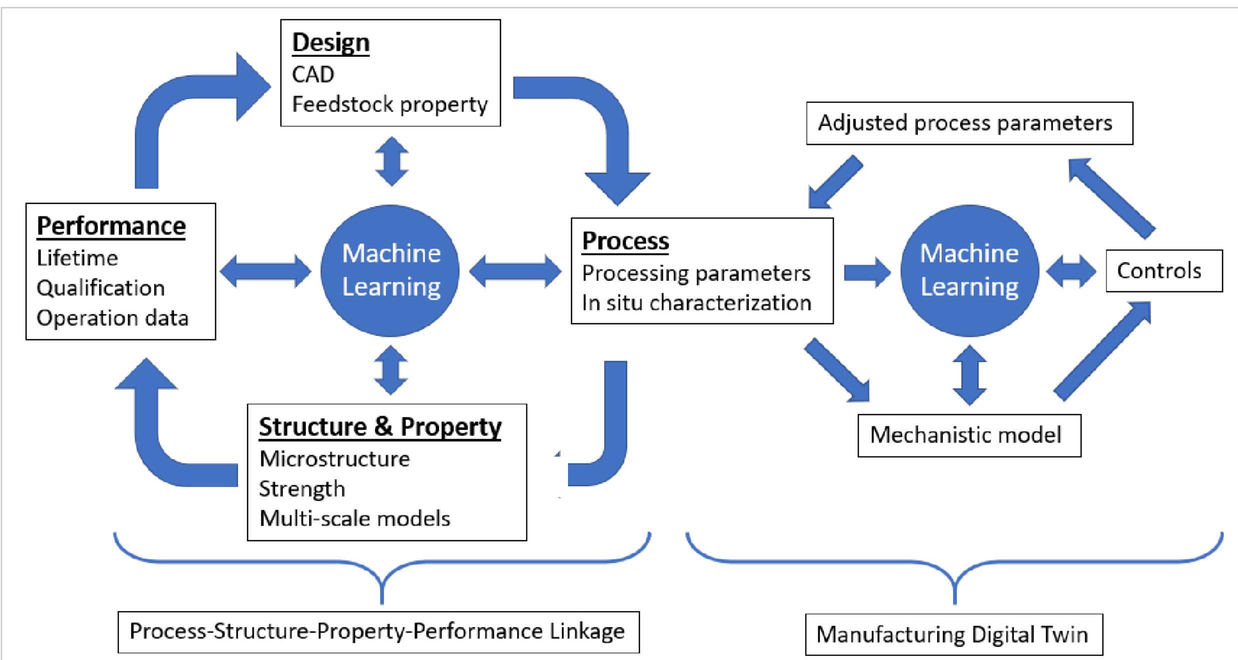

Figure 39. *Interaction between PSPP linkage and a manufacturing digital twin.*

6.1 BENEFITS OF MACHINE LEARNING

At the highest level, machine learning provides a new modeling method to supplement or replace aspects of the current modeling paradigm. Incorporating machine learning has the potential to accelerate the design and development of AMT components which will reduce costs. Listed below are examples where machine learning has aided the manufacturing process.

Design for AM involves creating a computer-aided design (CAD) model. Deviations exists between the CAD model and final product due to residual stress introduced by distortion in the manufacturing process [168]. Machine learning has been applied to counteract and incorporate the distortion in the CAD model to produce the desired component specifications [169]. Also, in the design step metal powder feedstock images were analyzed to develop correlations from powder characteristics (size, shape, and surface character) to porosity and defects [170], highlighting the link between the design and structure and property steps.

The digital twin is connected to the PSPP linkage through the processing step. The artificial intelligence and the modeling in the digital twin are enabled through machine learning. The benefit of using machine learning for the digital twin is to allow for dynamic control of the process to optimize the structure and properties. For AM, in situ characterization like visual images [171][172] and acoustic waves [173] have identified defects between deposition layers. This in situ inspection and analysis was performed during processing and adjusted process parameters to improve properties. Metal powder feedstock images were analyzed to develop correlations from powder characteristics (size, shape, and surface character) to porosity and defects [170]. Machine learning predicted tensile strength through temperature and vibration data during processing [174].

Mechanistic models also benefit from machine learning. Mechanistic models can estimate process phenomena and material properties like transient temperature fields, solidification morphology, grain structure, phases present, and defect concentrations based on well-established theories of physics, chemistry, materials, and transport [157]. Creating process-to-property linkage is challenging and involves complicated multiscale physics-based simulations. Many of the physical processes need to be represented in multiple length scales, and in some cases over varying timescales. Machine learning is a fast and reliable way to predict and optimize process conditions to achieve the desired properties [166]. For example, a neural network predicted weld bead height and width from wire-feed rate, travel speed, arc voltage, and stick-out for arc welding [159][175][176][177][178]. Johnson et al. [178] reviewed potential machine learning applications for advanced manufacturing. Some examples include using genetic algorithms to augment physics-based models to help with alloy design and feedstock selection. Genetic algorithms have been applied to alloy design for low and high-temperature structural materials, ultrahigh-strength steels, minimum defect structures, and exploring stable ternary or higher alloys. Genetic algorithms and neural networks were applied to find Al-Si compositions of minimum porosity [175]. Tapia et al. built a surrogate model for laser powder fusion of 316 L stainless steel. They used Gaussian process model to predict the melt-pool depth, velocity, and spot size [179]

Machine learning also supplements mechanistic models. Bikmukhametov and Jaschke investigated combining machine learning with process engineering to develop intuition about multiphase flow-estimation problems in the oil and gas production industry [177]. They discovered that linear metamodels, which combine physics-aware machine learning algorithms with raw measurement models, show the most accurate performance while maintaining good interpretability [180].

As noted above, the TCR is a prime example of nuclear technology and advanced manufacturing. The program also incorporated machine learning into its work. The TCR Program is an example of integrating these advantages by developing a digital twin to couple data analytics with design and manufacturing data for use in rapid prototyping and quality. TCR has already developed a data analytics framework for manufacturing; the four-step approach focuses on understanding the process, optimizing the process, creating a feedback loop, and certifying and qualifying the components.

Another application of machine learning is to propagate uncertainty. McDowell et al. predicted uncertainty for yield strength and minimum fatigue life through volume fraction of phases, crystallographic texture, and grain size [181]. The purpose of the study was to predict properties through the structure property linkage. The phase information and grain size inputs had uncertainty, and the uncertainty was propagated through the structure models into a Gaussian-process surrogate model. Gaussian process is a specific type of machine learning. The surrogate model was used to calculate the uncertainty in the final properties.

As digital twin modeling, PSPP linkage, and machine learning matures, the ability to predict the performance of the component will improve. Performance of components will inform the next iteration of component design until design matches performance. Data collected from experiments or operation will feed other steps in the PSPP linkage and improve machine learning models. Improved machine learning models will accelerate the targeted component design and will strengthen the knowledge base for applications to other components. Improved design will lead to better quality and reduced costs.

6.2 CHALLENGES OF APPLYING MACHINE LEARNING TO AMT AND NUCLEAR

Two primary challenges exist with applying machine learning to AMT and nuclear applications, qualification and correct application of machine learning. Qualification is the largest challenge because no clear path exists, and companies are hesitant to invest in machine learning if it will be rejected in the qualification process. Correct application of machine learning is a smaller challenge but should not be overlooked as machine learning is a rapidly progressing field and new algorithms are being developed.

6.2.1 QUALIFICATION

The NEI reported that the nuclear industry qualifies components, including the methods used to manufacture the components [37]. The NEI examined the qualification process for AMM components. This process also applies if the component was aided by machine learning during manufacturing. The NEI report explained the regulatory framework for AMM including qualification, regulatory requirements, and use of AMM without prior NRC approval. The report continues by examining possible regulatory pathways for AMM. The typical and perhaps most direct pathway to gaining regulatory approval is to make use of the ASME Boiler and Pressure Vessel Code (BPVC) language that has been endorsed by the NRC in 10 Code of Federal Regulations 50.55a. For situations where the ASME has not published Code language applicable to the AMM process or desired material, or where the Code approval and publication process is not consistent with industry-deployment timelines, a different pathway is warranted. The report describes two additional pathways in detail. The first pathway is to gain regulatory approval of AMM components building on ASME Code language. The second pathway is to demonstrate performance independent from ASME code activities. The report examines both pathways in detail and includes flow diagrams [37]. The reader is encouraged to review the report for more details.

ASME has identified the need to include digital engineering in standards by creating MBE processes. MBE will transform the industry by increasing productivity, quality, and profitability, and by reducing wasted effort and time, non-value-added work, lost information, missed opportunities, and time to market. MBE requires standards to provide digital datasets, frameworks, and workflows that facilitate high productivity and automation using a common set of information throughout a product's lifecycle, from initial idea to product retirement. The MBE standards committee meets quarterly to develop these standards [180]. In addition, ASME has created a new subcommittee under verification, validation, and uncertainty quantification (VVUQ) for machine learning. The charter for VVUQ machine learning is to coordinate, promote, and foster the development of standards that provide procedures for assessing and quantifying the credibility of machine learning algorithms applied to mechanistic and process modeling. Both of these efforts will aid in the clarifying the path forward for qualification.

Machine learning and digital twins will potentially play a role in the second pathway to demonstrate performance independent from ASME Code activities. The expected NRC approval involves demonstrating that the methods consistently produce high-quality components that satisfy the quality standards for nuclear components, and that those components can fulfill their function over their full design life with acceptable margins against failure. As described above, machine learning and digital twins will play an increasing role in AMM by accelerating the design and reducing costs. Machine learning models will be used in conjunction with performance data to satisfy the quality standards. Machine learning analysis from the processing data will help identify margins against failure. Hensley et al. provided a qualification example for 316 L stainless steel components made by LPBF AM. They examined three potential pathways: 1) AM followed by hot isostatic pressing to remove defects, 2) AM with in situ characterization in conjunction with modeling, and 3) AM with integrated computational materials engineering on the processing parameters. They found that for most of the samples following the first pathway, the AMM manufactured components were comparable to base values and would meet the requirement set by the standards committee. One sample had low strength and elongation; thus, more study is needed. The second pathway identified that optical imaging of defects would be feasible for model-based qualification. The third pathway modeled heat transfer as a function of laser scan, defects concentration with optical imaging, and densification during hot isostatic pressing, with the end goal of predicting tensile deformation and toughness. The next step is to include these physics-based models into a digital twin. Optimizing the processing parameters within the digital twin would lead to components with the required quality [182].

6.2.2 APPLICATION OF MACHINE LEARNING

With evolving technology comes opportunities for new failure modes. Potential gaps for machine learning can be categorized in two ways: correct implementation of the algorithm and correct physics-based modeling. For physics-based modeling, machine learning models need to be explainable and understandable. Machine learning is often described as a black box; however, for nuclear applications, intuition needs to be accessible from the models. Two recent Python modules (PySR and PySINDy) help remove the black box from machine learning and apply intuition. They fall into a category of methods called symbolic regression. The purpose of symbolic regression is to create an algebraic expression that approximates the data. The algebraic expression provides the intuition. Symbolic regression is an open field of research and new methods will be discovered over time. Another potential gap for physics-based modeling with machine learning is errors due to extrapolation. All machine learning models need to be kept within the boundary of the training data.

In terms of correct implementation of the algorithms, a potential gap is correctly fitting the machine learning models. Over- and underfitting in machine learning will lead to errors. Overfitting describes the machine learning model's predicting the signal as well as the noise. Underfitting occurs when the machine-learning model struggles to reproduce the training data and new observations. A good machine learning model is balanced between over- and underfitting. One method to find the balance is to use a technique called regularization. Regularization adds a penalty as the model complexity increases.

[NR1] Nicolas, Andrea, Chakraborty, Aritra, Paulson, Noah, & Messner, Mark C. Survey of Modeling and Simulation Techniques for Advanced Manufacturing Technologies Volume I – Predicting Initial Microstructures. United States. https://doi.org/10.2172/1688433

7 | CHALLENGES FOR AMTS IN NUCLEAR

While generative designs and adoption of new advanced manufacturing are being pursued by other industries (e.g., aerospace, defense, biomedical), they have yet to gain traction in the nuclear power industry. There are likely three reasons for this:

1) The change from established and optimized production methods have understood costs and production requirements. Changing to a new AMT technology will incur different costs and transition costs. These new costs will tend to discourage applications in a conservative
2) Shortage of materials information: Current nuclear energy manufacturing enterprises do not have access to knowledge and research information on how components prepared with new manufacturing processes will perform under high-radiation environments. [125]
3) Dearth of verifiable qualification of manufactured components to describe their fitness for overhaul: There is a scarcity of confidence on the qualification of components made by these methods, and there are no case studies validating the effectiveness of the technical and business value proposition for the nuclear industry. [125]
4) Issues related to a lack of supply chain for nuclear-related stock materials. (Especially for exotic nuclear materials) is also a big concern in the nuclear industries.

AM technologies bring a variety of benefits but are ineligible for nuclear applications because the AM processes are not being qualified quickly enough. Many distinct AM technologies are entering the market yielding heterogeneous results between materials, process parameters, and postprocessing treatment. Heterogeneity is increased by small anomalies in production resulting in low confidence in AM parts for high-risk applications. Previous sections discuss many of the benefits of nuclear, but these applications and benefits do not address and only amplify the need for large-scale qualification of AM materials and processes.

Traditional methods for structural material qualification are based on large-scale industrial production processes that do not have the versatility of AM. Therefore, existing qualification methods are slow and restricted and generally incompatible with the agility of advanced manufacturing. The strengths and weaknesses of AM, specifically flexibility and consistency respectively, are not accounted for which has resulted in the general exclusion of AM use for structural applications. Efficiency and versatility are essential for modern manufacturing techniques and the qualification standards must adapt to reflect this.

Numerous AM technologies are entering the market at an accelerating rate requiring a new approach to licensing them. The current materials standards focus on quantifying the minimum material properties for each material production process which has worked with relatively few processes. However, this would become overwhelming with the number of new AM processes that can produce bulk structural materials. One suggested new approach is that by switching the standardization process from process performance to product/system performance, it would allow a vast simplification of the licensing approach. Creating standards that encompass certain product performance requirements would allow limitless manufacturing processes to be categorized into a finite number of categories based on their performance. (Figure 40). This may streamline standardization while allowing more effective use by engineers who could choose materials based on their functional properties instead of having a few well-known alloys that may not be the best fit for the application.

The lack of adoption of AMTs in the nuclear industry has presented opportunities for a variety of innovative solutions to come forth resulting in a wide variety of technologies at different technology readiness levels (TRLs). Although this has brought benefits, it results in a general uncertainty in AM materials which requires dedicated and focused development and qualification to overcome. Companies will likely try to qualify their materials and production processes as soon as possible to create incentive for use of their process, even if they are currently immature technologies. Currently, the AMMT program of the Department of Energy's office for Nuclear Energy, is focusing on multiple activities to accelerate qualification and deployment of AMTs. More information on these activities will be made available through the 2022 financial year. The authors propose an AMT benchmarking exercise through joint collaboration requiring many samples to be submitted from multiple machines for independent testing. A benchmarking exercise will act as a cost barrier to a single company and also accelerate qualification.

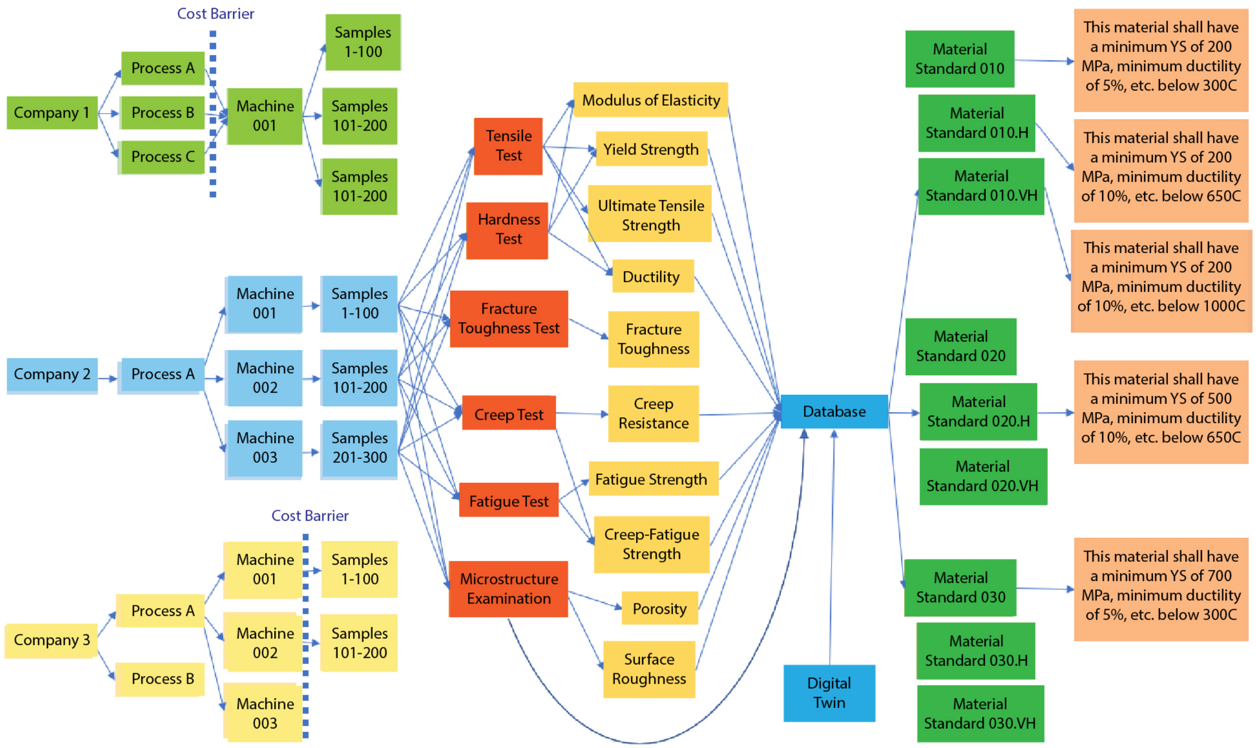

Figure 40. *A flow chart showing how a AMT process might be used in a benchmarking exercise for accelerated licensing.*

8 | CONCLUSIONS AND FUTURE SCOPE

AMTs show promising advantages in freedom of design, cheap mass-customization, rapid prototyping to production, the capability to produce gradient compositions, phase and grain size modulation, certain types of performance enhancement (e.g., radiation swelling), reduction in energy utilization, and ability to print even more complex 3D structures with minimum waste. Here, a comprehensive review of AM methods including advanced engineered surface coatings, materials, and the current state in trending applications in nuclear industries have been carried out. The main challenges that are attributed to the nature of AM printing have also been mentioned.

Innovations in AMT have already helped several critical energy and aerospace sectors. AM technologies become more and more prevalent in the aerospace, energy storage (battery and supercapacitor), oil & gas industries with applications, including onsite manufacturing of required components, and slashing multiple levels to save time and costs. In nuclear industries, AM have been expended to build nuclear core components with better materials performance in harsh reactor environments. The development of AMTs can be used for stimulating the accomplishment of field-fabrication of nuclear modules for advanced reactors, such as microreactors, and SMRs. With the rise of automation and artificial intelligence in AM technologies, co-design of printed electronics within one package becomes possible, making smart, IoT, advanced digital devices (such as implanted nuclear sensors within the reactor or fuel etc.) instinctively flexible and autonomous. Optimizing the processing parameters within the digital twin would lead to components with the required quality [180]. Another application to machine learning is to propagate uncertainty.

However, several challenges remain when it comes to the qualification, licensing, and manufacturing of marketable products in the nuclear industries. Further research and development initiative would help to overcome these key technical challenges, with huge expansion of the materials for AMT in the future, that will comprise composites, functional materials, active and biological materials, and implanted micro/nano sensor and devices. The fundamental research on the stability of AM parts used in the extreme high-temperature and hostile radiation environments, including high pressure, erosion and wear, fatigue, and the presence of wreckage and debris, is indispensable to the extrapolation of materials performance, properties, and lifetimes.

This review focuses on AMTs capable of producing parts appropriate for nuclear and related harsh environments and applications. Therefore, the following categories are considered out of the scope of this document in the interest of brevity and efficiency.

1) **Mature manufacturing processes:** Mature manufacturing processes that are already well integrated into the NPP supply chain do not require the focus of this document to highlight their underutilized potential for nuclear applications.
2) **Non-nuclear components:** Manufacturing processes for production of common components that may be essential for NPP operation but are not exposed to specifically nuclear environments are considered relevant for this review (e.g., computers, wiring, user interface hardware, facilities, etc.).
3) **Incompatible materials:** Manufacturing processes restricted to materials that are incompatible with nuclear environments are not included in the scope of this document. These include low-temperature materials such as polymers.
4) **Computational modeling:** Lately, huge efforts have been made to understand the fundamentals and underlying physics using advanced computational methods and modellings. Computational models, such as, statistics formula, density functional theory, volume of fluids, Lattice Boltzmann methods (LBM), and

molecular dynamics, atomistic modeling approaches, and finite element analysis have been applied to predict temperature distribution and evolution, material deformation, molten pool size and dynamics, and nanocluster-reliant material behaviors and characteristics. By tailoring AM parameters, the microstructure and properties of AM components can be tuned to meet the requirement of nuclear energy and other energy systems operating under harsh conditions.

Finally, in the nuclear industry, refractory metals and ceramics address a more challenging service environment, as extreme high-temperature carries higher energy efficiency as well as potentially higher rates of corrosion and degradation. The AMT of these metal-ceramic composites and their applications in the nuclear systems could be a hot research area in the future.

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